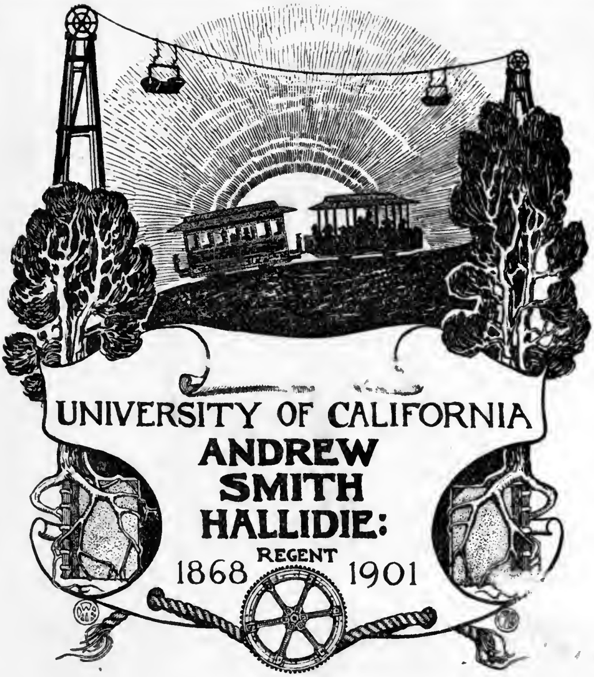
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THE

PRACTICAL PHYSICS

OF THE

MODERN STEAM BOILER.

THE PRACTICAL PHYSICS OF THE

Modern Steam Boiler

BY

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WITH A PREFACE

BY

PROF. R. H. THURSTON,

Cornell University.

WITH 314 ILLUSTRATIONS.

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PREFACE.

My purpose in this book is to give prominence to the fundamental principles which affect the form and the action of steam boilers. So many excellent treatises have been published which deal with the regulations concerning, and the structural details of, boilers of the cylindrical type ; in a word, with what may be called the Mechanics of the steam boiler (*i.e.*, treating of the boiler as a machine), that it has seemed to me useless to repeat chapters on strength of materials, on riveting and joints, and on numerous other interesting and important matters. I have not thought it necessary or advisable to follow that well-beaten track, but have endeavoured to take another path, as guided by the indications of physical research towards the goal of a fuller understanding of the actions involved in steam raising, and of the requirements of efficient boilers.

Thus the pages of this book are occupied with the practical Physics of the steam boiler (treating of the boiler as a heat engine), and deal more particularly with that which may be termed the modern form, the water-tube boiler. My aim in them is therefore not so much to treat of how boilers are made, as to consider on what lines they may be improved.

One consequence of the adoption of this aspect of the subject is that our point of view is changed as to several of its departments. Thus, as to the fuel, instead of the point being the relation of the quantity consumed to the area of the grate

surface, enquiry is directed to the question, what is the largest quantity which can be efficiently burned in given time at the highest temperature attainable (with or without a grate, in the ordinary acceptation of the term), and with the minimum of labour ?

With regard to furnace and flues, the point of view is changed from the number of inches of vacuum or plenum existing at various points in furnace, flues or chimney, to the number of feet per second velocity at which the hot gases traverse the heating surface. As to the heating surface itself, instead of (as formerly) regarding the fixed ratio between heating surface and grate area, we are led to enquire what is the proportion which the number of heat units transmitted per hour, from fuel to water, bears to the area of heating surface ; and as to the water, the question of importance is not now, what is the velocity of flow produced by the action of boiling in certain boilers (that, if observed constantly, may be a good criterion of the distribution of temperature in a given boiler) but it is, what is the greatest speed of movement which we can conveniently impart to the water, in a direction contrary to that in which the hot gases are travelling ? Again, in former days, the question of stresses was regarded almost exclusively from the point of view of the external structure of the boiler ; now, however, it is recognised that many of the most important consequences to the safety or life of a boiler may result from strains or stresses set up in the internal structure of the metal, whether accompanied or followed by other physical or chemical action, and consequently our point of view here also is altered.

The consideration of such questions necessitates some acquaintance with the physical principles which govern the actions whose sphere is the boiler, and I have consequently endeavoured to give some account of investigations which throw light in that direction.

Evidence is not wanting that we have entered upon an era of more scientific practice in steam raising than used to be the rule,

and, that being so, any measure of enlightenment as to the laws which must be obeyed in such practice is sure to be useful.[1]

The fact that such methods of treatment of an engineering subject as the present one are needed, or are likely to be welcome, may be taken as a hopeful sign that the breadth of the basis upon which engineering as a profession rests is beginning to be acknowledged.

To be an Engineer can no longer be held as equivalent to having a mere possession of certain recognised methods, either of calculation or of executing work. The foundation of all good practice must ultimately be an intelligent appreciation of natural phenomena and laws, in as far as these have been observed or discovered. And the man who can most fearlessly and thoroughly make, in his practice, an application of true principles, (which he may have learned in connection with widely different circumstances) in order to reach some desired result, is sure to be the most efficient Engineer.

The time was when a book on boilers would not have been regarded even with patience, unless it dealt with accepted practice and dwelt on its advantages ; or, at most, showed how some few details might be improved. Now, however, the desire is becoming wide-spread to know in what direction it is possible generally to progress ; and it does not take long in these days for any path to become a beaten track, after it is once marked out.

Fortunately the time has nearly gone by when ideas which belong to the physical, rather than to the mechanical, side of an engineering problem, can be dismissed by means of a cheap sneer at "theory," for all intelligent educated men have come to understand that practice without theory is a mere automaton, possessing no vital principle. In the days, not yet ancient,

[1] While the sheets of this volume are going through the press a paper by Mr. John C. Parker, "On the Science of Steam Raising," has appeared in the Proceedings of The Engineers' Club of Philadelphia, and I hail its publication as most valuable corroborative testimony to the accuracy of these observations, as well as to that of the direction in which improvement must be sought.

when "the practical man," so-called (but who was, more correctly, the man who had learned a certain routine of practice, beyond which he could not see and did not believe), was all-important; it was enough for any one to be known as "a man with ideas" to be at once condemned as a visionary. That *régime* had not the same sway in other countries, such as America, as it held in Britain, but even here there were enlightened men in the ranks of Engineers who never submitted to it. Happily it is now passing away. Sir William Fairbairn thus writes (in his "Useful Information for Engineers," third series, page 65) :—

"It is absurd to talk against theory, as if a knowledge of the exact science was a dangerous and a useless attainment; nothing can be more erroneous than this impression, as on close inspection there is no practice without theory, any more than there is any effect without a cause. In the useful arts theory can only be considered dangerous when it is not reducible to practice, and where it tends to error or false principles, which, in fact, is not theory but assumption. The true meaning of the term theory—which creates so much alarm in the minds of practical men—is neither more nor less than a series of definite rules by which practice is governed, and through which we derive, from fixed and definite laws, those sound and unerring results, which of all others is the primary object of practice to accomplish. Let us, therefore, abandon the 'rule-of-thumb' system, and cultivate true principles which should never be separated from the twin sisters of Science and Art."

Thomas De Quincy gives, in his "Miscellaneous Essays and Logic of Political Economy" (vol. xii., p. 333), a translation of Kant's essay "On the common saying that such or such a thing may be true in theory, but does not hold good in practice," the following extract from which may well be placed alongside of Sir Wm. Fairbairn's pithy remarks :—

"It is far more tolerable that an unlearned person should represent theory as superfluous for the purposes of his imaginary practice, than that a shallow refiner, whilst conceding the value of theory for speculation and scholastic uses, should couple with this concession the doctrine that in practice the case is otherwise; and that, upon coming out of the schools into the world, a man will be made sensible of having pursued mere philosophic dreams. In short, that what sounds well in theory is not merely superfluous, but absolutely false in practice. Now the practical engineer who should express himself in these terms upon the science of mechanics, or the artillery officer who should say of the doctrine of projectiles, that the theory of it was conceived indeed with great subtlety, but was of little practical value, because in the actual

exercise of the art it was found that the experimental results did not conform to the theory, would expose themselves to derision. For supposing, that in the first case, should be superadded to the theory of mechanics that of friction; and that in the second, to the theory of projectiles were superadded that of the resistance of the air—which in effect amounts to this, that if, instead of rejecting theory, still more theory were added—in that case the results of the abstract doctrine and of the experimental practice would coincide in every respect."

In the following pages I have adhered to my usual practice of endeavouring in every case scrupulously to acknowledge the source of my information, either in foot notes or in the text. In doing so I no doubt expose myself to the criticism that a portion, perhaps even a large portion, of my writing is not original, but I prefer that to the meanness (which is, unfortunately, too often met with) of appropriating the thoughts or words of another without acknowledging their author, or to the vanity which makes use of borrowed plumes in the delusive hope that the fraud will not be detected by those who are well informed.

It is certain that only a few can possess the means or the opportunity for independent research (just as no one man could invent all the different boilers described), and consequently that the majority must be content to learn from them, using the results of investigations analytically or synthetically, as illustrations or as a basis for deduction. It is a mistake to think that there can be no originality in such a use of these results. On the contrary, in these days invention and improvement must in the main proceed in the direction of the adaptation of materials and knowledge already accumulated.

The major part of this book was written early in 1898, but its completion was delayed by the necessarily tedious examination of patent office records which was required for the preparation of Chapter VIII. Such an examination, in addition to affording historical data, furnishes proof that whilst there must be progress in knowledge and skill, the attempt to intrude the term "evolution" into engineering science is an erroneous one. However plausible the theory which is denominated by

that term may be, as applied to organic structures considered from a human standpoint, it can have no proper application in engineering as regards either inventions or the inventors themselves. As to the former, some of the oldest inventions are found to display the most advanced ideas, and, with regard to the latter, it has repeatedly been shown that nearly all great improvements have been introduced from the outside of the special branch of engineering to which they apply. Development and refinement are undoubtedly found, but these apply either to the form, or to the completeness of the detail, of structures or machines of kinds the use of which is continued long enough, or repeated frequently enough, to permit of experience being gained with them. "Environment" in engineering resolves itself into a question of that experience, combined with the essential elements of the quality of the materials and the methods of construction, which are available at any given time. These latter have undoubtedly exercised the principal influence on development, and we find that many modern ideas of design are merely old ones revived under circumstances in which both the means of carrying them out successfully and the opportunity for their being employed profitably have come into existence.

Since the completion of the manuscript of this volume a Committee to investigate the subject of the water-tube boilers in the Royal Navy has been appointed by the House of Commons under the recommendation of the Rt. Hon. G. J. Göschen, then First Lord of the Admiralty; and after some months of enquiry a preliminary Report has been issued. The period of experimental trials of different designs of water-tube boilers has since then been entered upon, and it is probable that a further Report will emanate from the Committee, although not for a considerable time.

It was to be expected that a Committee, nominated in consequence of political pressure, would not in its constitution prove entirely satisfactory to the engineers and experts of the

country; yet, although the chief qualification for appointment to this Committee seems to have been engineering skill combined with an absence of special experience of water-tube boilers, there are few who can object to the main direction which the recommendations of the Committee have so far taken.

Whether a satisfactory solution of the water-tube boiler question can be reached during the lifetime of this Committee remains to be seen.

In this connection the remarks in a paper by Mr. John C. Parker, of Philadelphia, "On the Science of Steam-making" (published while this book is passing through the press), deserve some attention.

My best acknowledgments are due to Professor R. H. Thurston, of Sibley College, Cornell University, Ithaca, N.Y., U.S.A., not only for much information derived from his various technical works, but also for the kindness with which he consented to write an introductory note to this volume.

I am also indebted to many manufacturers of boilers for information about their special generators, and for the loan of woodcuts required for illustrations; and to some personal friends for valuable assistance and advice in the work of preparing this book. Amongst the former are the Councils of the Institution of Civil Engineers and the Institution of Engineers and Shipbuilders in Scotland; Messrs. Willans and Robinson, Ltd., Henry Watson & Sons, Simpson & Bodman, The Actiebolaget de Lavals Angturbin, Robertson & Outram, Clarke, Chapman & Co., Ltd., Haythorn & Stuart, B. R. Rowland & Co., Ltd., R. Hornsby & Sons, Ltd., Prof. W. H. Watkinson, Mr. J. W. Reed and Mr. R. Dunell; whilst amongst the latter are Prof. E. J. Mills, D.Sc., F.R.S., Mr. J. T. Milton and Mr. E. H. Parker.

I wish also to acknowledge the assistance rendered by my son, Mr. Stephen Rowan, in the preparation of drawings for some of the illustrations.

INTRODUCTORY NOTE.

By Robert H. Thurston, LL.D., Dr.Eng'g.; Past-President American Society Mechanical Engineers, &c.; Director of Sibley College, Cornell University.

In the selection of his title, "The Practical Physics of the Modern Steam-Boiler," the author has admirably defined his field of exposition. It is a field, also, which offers a large opportunity, and Mr. Rowan has well availed himself of it, greatly to the advantage of the reader, professional as well as novice. He has so treated his subject as to lay large stress upon the distinguishing adjective in his title, "*practical*," collecting information from the world's literature of engineering bearing upon the practical development of the art of steam-boiler construction and on the practical applications of scientific principles. The book is not a systematic treatise covering the whole field of design, construction, and operation of every class of boiler; nor is it intended as such. It is a discussion of a defined and limited part of that great department of engineering, and its illustrations of fact and principle are very largely devoted to the modern types of "water-tube" boilers, while the purpose of its writer is declared to be quite as much the indication of the trend of improvement as the exhibition of their present status as apparatus for the evolution and storage of thermal energy.

The point of view of the author of this novel and valuable contribution to the literature of the subject is well expressed, and the purpose held before himself during its preparation is clearly defined, by the form given by him to the topics discussed. He would not seek to learn the ratio of fuel-consumption to the

grate-area, but rather the philosophical datum of real importance, the ratio of area of heating surface to fuel consumed. He would ascertain the conditions of maximum efficiency both of heat development and of heat transfer. He studies the effect of varying rates of flow of furnace gases along the heating surfaces with which they are in contact, with the purpose of ascertaining the laws of heat-exchange as affecting the efficiency of the boiler as a whole. He investigates the effects of chemical and structural changes, as well as of mechanically applied stresses, upon the safety and the endurance of the boiler. In the whole work, it is recognized that such a real and practical and applicable knowledge of this, as of any, department of engineering must be based upon scientific fact, principle, and method; discovering by experience and direct experiment the fundamental facts, deducing by sound logic the principles of which the facts are the illustrations; then applying that knowledge of fact and those accurately defined principles to the solution of the equally well-defined problems of the engineer.

The modern and professional, as distinguished from the older and unscientific, methods of engineering are thus illustrated. The engineer of the twentieth century designs rather than invents, and secures a certainty of success by systematic and scientific method, first seeking an exact definition of his problem, then proceeding to its solution by application of deduction or computation to each element of the case in a perfectly well-settled order of sequence. Engineering is to-day a more exact science than is any other among the professions or the vocations of our modern world. Its practice involves larger and more exact knowledge of nature's laws and of facts related directly to its tasks; its schools, where most developed and best adapted to their purposes, demand more of the immatriculates, and more and harder work for their diplomas and certificates, than do the schools of the so-called "learned" professions. Engineering has already conquered its place beside those especially honoured guilds, and, such are the requirements of the modern industrial world, it must soon make itself the most learned of the professions, in the departments of applied science, if not otherwise.

The best engineering is that which avails itself most intelligently and most universally and invariably, in every task, of exactly known facts and precisely formulated principle. It

employs exact knowledge rather than "rule-o'-thumb." Where exact knowledge is not attainable, however, it does not hesitate to use a "rule-o'-thumb" system, however crude, if it seems reliable and has been found by experience to be safe and economically satisfactory. Like any well-trained physician, the engineer employs the best means at hand for the accomplishment of his purpose, and without stopping to inquire into its authorship.

In the treatise here presented to the engineer interested in steam production, I am much interested in finding so large a portion of the work devoted to the water-tube boiler. In a report to the American Institute of the State of New York, in 1871, as chairman of a committee which, for probably the first time in history, determined the quality of steam supplied from water-tube and other boilers by condensation of their whole output during the trials, I wrote into the summary of conclusions this deduction, that we might even then "look forward to the time when their use will become general, to the exclusion of the older and more dangerous forms of boiler."*

Two fundamental principles have been enunciated by those famous engineers, John Stevens and William Fairbairn, which are more nearly complied with by the water-tube type of boiler than by the shell-boiler :—A boiler should be so constructed that it shall not be liable to explosion ; the boiler should also be so constructed that should it happen, through neglect and carelessness, inevitably here and there met with in the weak humanity which must be entrusted with it, that explosion does occur, the explosion shall not be dangerous. The consideration of these principles will be found to justify extended study of promising types. The remark of the author of this treatise that "there are solid grounds for the opinion that further improvement is possible" affords additional reason, if other reason seems needed.

The enormous aggregate of information, from authoritative sources, here collected is accompanied by much instructive comment and many helpful suggestions, and the book will be

* Transactions American Institute of the State of New York, 1871 ; Report of Committee appointed to test Steam-Boilers, Albany ; Argus Press, 1872. See, also, this volume, page 517.

found a mine of valuable and solid learning in this field. The facts gathered together, and the principles illustrated and elaborated, the numerous drawings of the most important inventions and constructions, and the systematic presentation of all, should prove useful to every class of readers.

The fundamental problem of the engineer in this department of his work, as in all other fields, is a financial one. Given a specific demand for steam ; to provide that quantity, certainly and safely and continuously, at a minimum total cost, including purchase and installation and capitalized current expenditure, for the life of the apparatus, together with all incidentals, whether gains or losses, however affected by the installation of the boiler. This means reduction of weight, of space occupied, of fuel consumption and labour costs, of preparation of foundations on shore and displacement of valuable cargo and passenger accommodation on shipboard, of transportation of supplies, and of removal of ash. This principle is most completely complied with when the installation contributes in a maximum possible degree to the dividend-earning capacity of the enterprise, of which it is a material element, and when the books of the treasurer show most satisfactory balances so far as affected by its use. The so-called boiler efficiency is an essential factor in this result, but it is by no means the only one. The engineer is thus necessarily, if successful, a financier of high rank, and his success must always be ultimately gauged by a monetary standard. There is always a certain proportion and size of boiler of any one class and type which affords a solution of this "problem of the golden mean." * In the attempted solution of this ultimate problem, the knowledge which may be acquired in the study of ascertained facts and of established principles, such as are here brought together, the engineer will find essential aid.

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* "Manual of Steam Boilers." Thurston. Chapter XIII.

SYNOPSIS OF CONTENTS OF CHAPTERS.

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THE PRACTICAL PHYSICS

OF THE

MODERN STEAM BOILER.

CHAPTER I.

INTRODUCTORY—GENERAL CONSIDERATIONS.

ALTHOUGH, in a popular view of the subject, the water-tube boiler is considered to be the product of evolution in boiler design, yet this is true only as regards the accepted employment of this form of steam boilers for marine work. Regarded from the point of view of design, the water-tube (tubulous or sectional) boiler is one of the earliest products of engineering, as directed to the construction of steam machinery. It rarely happens that the originator of any complete form of apparatus finds the ideas of men in general so far advanced, or their minds so receptive, as to induce them to adopt at once a new thing, the principles of which they have not grasped. In the main, ideas must rise from what is elementary, although incomplete, to what comprehends a larger view of the subject, but which, although it may be called complex, if judged superficially, is none the less simple when its wider range of principles is understood.

From very early days in the history of the steam engine, and of engineering as connected with it, there have been instances of men who have sought in their practice to carry correct principles of physical science to their rational conclusion. Usually, however, the apprehension of principles has preceded the existence of the means necessary for their practical application with success—not to speak of the general readiness of men's minds to accept them—and engineering has, in the case of

steam boilers, witnessed at least one example of this. So that these early attempts to reduce science to practice being often unsuccessful, general practice has been really governed more by facility of construction,[1] according to the existing state of appliances and materials, than by adherence to the principles which govern the working of the apparatus in detail. Doubtless also, there have been, and are, some who, pointing to the failure of early examples of a system of construction which is correct in theory, and to the comparative success of types more simple and rude, have argued for the continuance of these incorrect types and for the abandonment of efforts to arrive at a successful application of true principles. But the law of progress in human affairs forbids their being listened to beyond a certain point, and it is an axiom in mechanical, no less than in moral, affairs that *magna est veritas et prævalebit.*

There were, almost from the first, two distinct fundamental ideas upon which steam engine design and working were based, and consequently two distinct schools of men connected with these ideas of design. The one school, which is traceable through Von Guericke, Huyghens, Papin, Newcomen, Savery and Watt,[2] regarded the steam engine primarily as a vacuum engine, or apparatus by means of which the pressure of the atmosphere could be utilised, and the other school, comprising Leupold, Hornblower, Heslop, Bull, Trevithick and Woolf, regarded it as a pressure engine or apparatus for utilising the expansive force of steam at pressures above that of the atmosphere. In the case of the one form of apparatus, very low pressures of steam were used, the main portion of the work being done by atmospheric pressures acting upon one or, in turn, both sides of the piston ; whilst in the other form, the steam propelled the piston to and fro, and the exhaust took place at a greater or less pressure above that of the atmosphere.

In spite of the great names which have been associated with the former, it is more in connection with the latter that the development of the steam engine as a heat engine has been found to proceed—although the compound engine to some

[1] See "A Treatise on Steam Boilers, etc.," by Robert Wilson, A.I.C.E., pages 3–5. London, Crosby Lockwood and Co., 1877.

[2] See "The Steam Engine and Its Inventors," by R. L. Galloway. London, Macmillan and Co., 1881.

extent combines both principles—and it is the development of the use of high pressures of steam which has, in its turn, forced the question of water-tube boilers to the front and their general use upon the serious consideration of engineers.

In the nature of the case difficulties from want of suitable materials and from imperfections of manufacture were sure to arise, and have in the past frequently arisen; but in our days both the quality of materials and the power and capability of machine tools have been so vastly improved that less difficulty would now be experienced in constructing boilers to work at a pressure of 1,000 lbs. per square inch, than would, at the beginning of the century, have been met with in producing one for 100 lbs.

The ideas familiar to men in general have also progressed, and it is an undoubted fact that the subject of water-tube boilers occupies now a position very different from that which has been generally accorded to it at any period up till within the last few years.

As late as the year 1867, one writer on the subject said, at the close of an interesting paper, [1] "experiment daily demonstrates that there is no insuperable objection to the water-tube boiler, yet comparatively little or nothing is known about it by engineers or boiler-makers, and although the author believes that the principle has a great future before it, the subject is very far indeed from having as yet received the attention it deserves." That remark is happily not applicable now, although we are far yet from having a general acceptance amongst engineers and boilermakers of the correctness of the principles on which the design of good water-tube boilers should be based.

Regarding the tardy improvement in marine boiler design, Mr. F. J. Bramwell, speaking after compound engines had been well introduced and the economy arising from the use of steam of comparatively high pressure used expansively was well established, remarked in 1872, [2] that he had been "often struck by the indifference with which for so many years the constructors and the users of marine steam engines regarded the question of economy in fuel; and by the fact that, while wonderful progress

[1] "On Water-Tube Boilers," by V. Pendred, Trans. Soc. of Engineers, 1867.

[2] Proceedings of the Institution of Mechanical Engineers, Vol. for 1872, pp. 125–154.

was made in the increase of the speed of the ships, no one seemed to care about the quantity of fuel burnt, nor to look upon excess in this respect as a stigma on the profession of the mechanical engineer. So far as the marine engineer was concerned, the question of getting this economy was for many years beset with difficulties. The construction of the marine steam engine employed, and the form of boiler with it, were inconsistent with attempts at economy. The boiler was made, not so much with a view to strength, as with the object of stowage; and thus marine boilers became huge rectangular covered tanks, with fireplaces and flues all having flat sides, because, as was said, 'that figure gives the greatest cubical content in the smallest space.' Although engineers knew that the cylindrical shape was the strongest, yet even that form was not for a long time introduced into steam vessels, because it was held that "the most convenient form of the boiler is that it should be adapted to the shape of the boat, and that being taken for granted, the safety would depend upon the strength of the metal and not on the form." And again, "The construction of marine boilers for sustaining the higher pressures of steam now in use, is a subject of essential importance for efficiently carrying out the advantages of high expansion in compound engines, and the progress of their application was seriously impeded at the first by the unsuitability of the boilers in use at the time for carrying the higher pressures required."

In 1878,[1] the present author again expressed these views, especially with reference to the cylindrical boilers, which had by that time succeeded the "rectangular tank" form, and also pointed out in what respects they did not fulfil several conditions essential to an efficient steam generator.

Again, in 1887, the late Dr. A. C. Kirk, as President of the Institution of Engineers and Shipbuilders in Scotland,[2] said, on this subject, "So far as we have gone the saving effected in the weight of steam used to produce a given power has reduced the total weight of the machinery, although the scantlings are

[1] "On the Design and Use of Steam Boilers," British Association Reports 1878, p. 712, and *Engineering*, Vol. xxvi., pp. 164 and 283.

[2] "Transactions of the Institution of Engineers and Shipbuilders in Scotland," Vol. xxxi., pp. 10, 11.

heavier. From what we have seen, not only has there been a reduction in space occupied, and in the weight of coal and machinery, but there has been a saving both in the weight and in the space occupied by the machinery alone, and fewer men are required to work it. . . . As to the future, without setting up as a prophet, I may, I think, venture to predict that it is in the boiler rather than in the engine that the next great step will be made. What that step will be I dare not venture to foretell, but I would not have it be imagined that, because the water-tube boilers of the 'Propontis' gave out after a time, the water-tube boiler cannot be revived.

"More is known of the management and action of boilers than was known then, and those in charge have learned more, with the result that what was not then a success[1] may contain the germs of success now. I commend the steam boiler to the attention of all my hearers."

Even as late as January, 1897, we find the author of a paper on "Suction Draught" for boilers[2] awaiting "the advent of some more commercially successful type of water-tube boiler than any of the present forms," and thus expressing the idea that we have not reached the limits of improvement in boiler design. We shall endeavour to show in the sequel that there are solid grounds for the opinion that further improvement is possible.

In the past the special requirements of particular work have, or the duty required in special circumstances in practice has, exercised an influence in developing designs in certain directions. Thus the earliest development of steam carriages for locomotion on roads brought into existence several forms of water-tube or sectional boilers, because the great desiderata for that special purpose were extreme lightness and rapid steaming power. The development of railways and the conditions under which locomotives work on them have created for us the distinct form known as the locomotive boiler, and mercantile steam navigation has called forth in succession the "rectangular tank"

[1] For the reasons of this want of success in that instance the reader is referred to the "Transactions of the Institute of Engineers and Shipbuilders in Scotland," Vol. xli., pp. 117-121.

[2] "Transactions Institute Engineers and Shipbuilders in Scotland," Vol. xl., p. 107.

boiler, the "haystack" boiler and the cylindrical, "drum" or "Scotch" boiler, whilst the requirements of ships of war and especially of torpedo craft, have recently brought forward various forms of water-tube or sectional boilers with mechanically produced draught, possessing the features of extended surface, small weight per indicated horse power, and great steaming power.

It will no doubt ultimately be found necessary to go outside of and beyond such requirements of special conditions of work in designing boilers, and, as led by the results of investigation into the physical conditions under which transference of heat and generation of steam should take place, to proceed on the basis of a more intelligent appreciation of physical facts, and with more complete provision against loss or waste of the energy which we wish to employ usefully, than has been possible hitherto. Enquiry into the phenomena of, and investigation of many of the questions connected with, the action of steam boilers, have recently been prosecuted with considerable vigour, and it is to be hoped that the outcome of such research will be to illuminate a larger portion if not the whole of the field of boiler action, by means of which engineers may be able to understand clearly what are the physical conditions for which they have to provide in designing a steam boiler.

The kind of advice usually given in text-books on boilers with reference to boiler design will, it is also to be hoped, soon change, and instead of our having "custom, the kind of water used, and the cost and quality of fuel in a given locality," urged as the proper factors to determine the kind of boiler which should be used there, our "custom" will rather be to know how to treat any kind of water and any quality of fuel so that the most economical results can be obtained from them in a proper *form* of boiler. We are sometimes told that "deviation from common practice is bad and should be made only for sufficient reasons," but that is in one sense bad advice, because it assumes that common practice has reached the summit of perfection, instead of its being itself the thing which constantly needs to be elevated. Such advice disparages improvement and puts an inadequate and really pusillanimous standard before young engineers, tending to destroy or suppress independence or originality of thought, and to teach them to seek ignoble ease under the safe

shelter of a popular acceptance of erroneous notions. The only sense in which the advice should be adopted is that in which the room for improvement is constantly accepted as a "sufficient reason" for a continuous effort to "deviate from common practice." In a recent work on Boilers the general features which are to be looked for in all boilers are set forth, and we are told that whatever may be the type of boiler chosen for any particular work or locality there *must* be provided the following :—

1. Sufficient grate area to burn the fuel required under the available draught.

2. Suitable combustion space to properly burn the fuel.

3. Sufficient area of flues or tubes to carry off the products of combustion.

4. Sufficient heating surface to absorb the heat generated.

5. Proper water space to prevent too great a fluctuation of the water level when there is an irregular demand for steam.

6. Suitable steam space to prevent too great a fluctuation of pressure when steam is taken at intervals, as for the cylinders of a steam engine.

7. Sufficient free water area for disengagement of steam.

Such a statement of the case is, however, most imperfect, and the omission of all consideration of several essential elements in boiler design and working renders it useless except under the conditions of the use of a certain kind of boiler.

In fact the authors themselves dismiss most water-tube boilers as unsuitable on these grounds: "The last three conditions are not fulfilled by most water-tube boilers; some such boilers depend on a separator for disengaging steam from water"; and evidently the only good water-tube boilers, according to this criterion, would be those which depart least in design from the cylindrical or other tank boilers.

But it is worth considering whether under altered conditions such a summary of necessary conditions may not wholly disappear. Thus as to

1. What if it is found better to dispense altogether with the existing arrangement of grates and to introduce methods of combustion widely differing from those at present in use which necessitate both "grates" and "draught"? Even with gaseous fuel no grate would be required.

2. When fuel is burnt it is a truism that there must be suitable combustion space provided for the operation, but we are not informed in the statement of this requirement under what conditions the fuel is to be burned, and therefore it follows that what might be suitable in one method of combustion would be quite unsuitable for another.

3. To be properly stated this condition should have informed us at what velocity, under what pressure, and at what temperature the products of combustion are to be carried off, as these elements would cause wide differences in sizes of exits wanted; and similarly in

4. We should be informed *at what rate* the heat generated is to be absorbed by the heating surface. There is a wide difference in this matter between what is theoretically possible and the best that has as yet been done in boilers.

5. As to this we need to ask, "fluctuation" where? In a gauge-glass or column outside the boiler, or in the boiler itself? The latter evidently is meant, but our ideas of a large surface of water, broken only by the appearance of bubbles and momentary upheavals of small portions of the surface, are quite foreign to what is no doubt proper to a boiler as a *steam generating machine*, in which the essential condition is that the whole of the water in the boiler should be kept in continuous and rapid motion.

6 and 7 are simply corollaries from 5, and if they do not simply mean that boilers of sufficient size to supply the power needed must be provided, they proceed, as does 5, on partial and incomplete views of what proper steam generation may require. Why, for instance, should it be assumed that "free surface" (so-called) is better for disengaging steam from water than the use of some form of separator? What principle that is correct is in action where "free surface" exists that cannot be introduced into, or employed in, a separator? It is evidently a simple question of counteracting the effects of rapid motion, so as to permit of the action of gravity which causes fluids of different specific gravities to separate from one another. The "free surface," where the water is clean, permits the operation of the action of gravity to take place in one way, and the separator, when it is an efficient one, provides for that action in another, but not necessarily a less efficacious way.

At present, we may venture to assert that the following are demanded from a good boiler, and that they afford a criterion by which boilers can be compared and judged :—

1. The maximum of heating surface in proportion to weight.

2. The maximum of strength with minimum thickness and weight of material.

3. The maximum of strength due to the form without artificial support, such as from stays.

4. The maximum of circulation of the water inside.

5. The maximum of circulation of the gases outside.

6. The maximum of transference of heat from the gases to the water per unit of surface.

7. The minimum of weight in proportion to steaming power.

8. The minimum of fuel consumed per effective horse power.

9. The minimum of water delivered with the steam.

10. The minimum of heat delivered into the atmosphere.

The proof of these things will come up in detail as we investigate the subject, and we shall probably get an approximate idea of the best that is possible, by means of which we can institute a fairly true comparison between rival boiler designs.

CHAPTER II.

SOME FUNDAMENTAL ELEMENTS OF BOILER DESIGN.

THERE are certain elements of boiler design which, being fundamentally necessary, are permanent and unaffected by modifications which may require to be introduced as certain physical actions or laws become better understood. We are plainly concerned with the laws of fluid pressure ; with those connected with steam as a gas which requires a considerable expenditure of heat for its formation and maintenance at pressures of several atmospheres, at which it is capable by its expansion of producing great dynamical effects, and these must be provided for. There are also considerations connected with the *use* of boilers which impose some necessary conditions on all designs.

Fluid Pressure. — According to Pascal's law of fluid pressure, disregarding the effect of gravity, the pressure is transmitted undiminished in all directions, and acts with the same force on all equal surfaces, or proportionally to the area of the surface of any part of the internal walls of the vessel, and in a direction at right angles to the surface. In the case of cylindrical vessels containing fluid under pressure, the pressure per square inch on the vessel multiplied by the number of inches in the circumference, gives the total stress exerted on a ring of the circumference an inch wide.

Strength in Relation to Form and Dimensions.—The foregoing refers to pressure exerted radially in all directions, and is not to be confounded with the measurement of the force tending to split the cylinder longitudinally. As to this latter, it is dealt with in many works on applied mechanics, and on boilers. Mr. R. Wilson (in "A Treatise on Steam Boilers," London, 1877), for instance, says that the force tending to rupture the unit length of the cylinder of a boiler longitudinally, is represented by multiplying the diameter by the pressure on each unit of surface. The total amount of force tending to divide the cylinder in lines parallel to its axis is therefore found by multiplying the

above product by the length of the cylinder. The manner in which this strain is borne by the material of the boiler greatly depends on its thickness. "When this is considerable, compared with the diameter, as in hydraulic presses and cannon, the inner layers of the material are more severely taxed than those on the outside. This difference may be so great, that the latter render no material assistance to the former. . . . The strength of a cylinder to resist transverse pressure is therefore proportionate to the thickness and is represented by the tenacity or tensile strength of the material, multiplied by the section on both sides, or twice the thickness multiplied by the length."

It is easy to see, therefore, the great gain in strength which is obtained by reducing diameters and thicknesses, and this fact points distinctly to the fitness of water-tube boilers for withstanding high pressures.

Another advantage that is gained by the use of small diameters is that as there is less departure from truly circular forms, there is less opportunity given to the pressure to produce deformation of the boiler. Boilers of large diameter necessarily depend, for strength to resist pressure, to a considerable extent, upon the material of which they are constructed, and hence, as the steam pressures in use have gone up, the thicknesses of shell plates have also advanced as far as possible with safety, first, with wrought iron and then with steel as the material.[1] The use of this thicker material, amongst other disadvantages, causes a greater difference in diameters between the various rings or longitudinal portions of the boiler shell, as well as between the shell and the lap or butt joints in it, and this accentuates the inequality of the stresses to which such shells are subjected. This subject has been frequently referred to in works on boilers, but seldom in more clear and forcible language than the following[2]:—"Emerson showed, more than sixty years ago, that the stress tending to split in two an internally perfectly cylindrical pipe submitted to the pressure of a fluid from the interior, is as the diameter of the pipe and the fluid pressure. He also showed that the stress arising from any pressure, upon any part, to split it

[1] See on "Experience in the Use of Thick Steel Boiler Plate," by William Parker. Trans. Inst. N.A., 1885.

[2] See "On the Wear and Tear of Steam Boilers," by F. A. Paget, C.E. Jour. Soc. of Arts, London, 1865, p. 388.

longitudinally, transversely, or in any direction, is equal to the pressure upon a plane drawn perpendicular to the line of direction.

"As in a boiler the thickness of the metal is small compared with the radius, the circumferential tension has been assumed to be uniformly distributed ; and the strain per unit of length upon the transverse circular joint, being only half that upon the longitudinal joints, the strength of the latter has been taken as the basis of the calculations for tensile strength of the joints. But in taking the internal diameter of the boiler as the point of departure, the internal section has been assumed to be a correct circle, which would only be practically true in the case of a cylinder bored out in a lathe, but never in that of a riveted boiler. Two of Emerson's corollaries from his first proposition have, in fact, been neglected. He showed that if one of the diameters be greater than another, there will then be a greater pressure in a direction at right angles to the larger diameter ; the greatest pressure tending to drive out the narrower sides till a mathematically true circle is formed. The second is, that if an elastic compressed fluid be enclosed in a vessel, flexible and capable of being distended every way, it will form itself into a sphere."

The strains put upon the shells of large cylindrical boilers, such as marine boilers of the "Scotch" or "drum" type, are further complicated by the insertion of furnaces and combustion chambers, which are stayed to the shell and ends ; and there are also the flat surfaces which are inseparable from boilers of large diameter as ordinarily made, and must be stayed together. These latter have equal pressure upon them only when these surfaces are equal, but this they very seldom are, and consequently there is an opportunity presented in their existence for the action of unequal pressure producing further deformation.

Deformation, Changes due to Pressure. — Some measurements of the actual amount of deformation of Scotch or cylindrical boilers observed at both working pressure and test pressure have been published by Mr. J. T. Milton,[1] Chief Engineer-Surveyor to Lloyd's Registry, and these show the extent of the deflections to be in general in direct proportion to the pressure applied, "being at the test pressure about twice that at the working pressure."

[1] "Notes on some Alterations of Form to which Boilers are Subject when under Working Conditions." Trans. Inst. N.A., Vol. xxxiv., 1893, p.157.

TABLE I.

	Boiler A.	Boiler B.	Boiler C.
Diameter of boiler (mean) ...	14 ft. 1 in.	15 ft.	15 ft. 3 in.
Length of boiler	10 ft.	9 ft. 9 in.	17 ft.
Working and test pressures ...	160 lbs. 320 lbs.	80 lbs. 160 lbs.	160 lbs. 320 lbs.
No. and description of furnaces	3 Purves.	3 plain.	6 Fox.
Diameter of furnace (outside)	3 ft. 3 in.	3 ft. 6 in.	3 ft. 11 in.
Length of furnace, over tube plates	7 ft.	6 ft. 6 in.	6 ft. 8 in.
No. of combustion chambers in boiler	3	3	3 each common to 2 furnaces.
No. of vertical rows of stays in sides of chambers	2	2	4
Thickness of shell plates ...	$1\frac{1}{8}$ in.	$\frac{11}{16}$ in.	$1\frac{11}{32}$ in.
Thickness of chamber side plates	$\frac{19}{32}$ in.	$\frac{1}{2}$ in.	$\frac{5}{8}$ in.
Thickness of chamber bottom plates	$\frac{7}{8}$ in.	$\frac{1}{2}$ in.	$\frac{7}{8}$ in.
Thickness of furnace plates ...	$\frac{15}{32}$ in.	$\frac{1}{2}$ in.	$\frac{17}{32}$ in.
Chamber tops stayed by ...	Girders.	Curved.	Girders.
Chamber bottoms	Not stayed.	Stiffened with ⊥ not connected to shell.	Not stayed.

OBSERVED ALTERATIONS OF DIMENSIONS.

	Boiler A. At working pressure of 160 lbs.	Boiler A. At test pressure of 320 lbs.	Boiler B. At working pressure of 80 lbs.	Boiler B. At test pressure of 160 lbs.	Boiler C. At working pressure of 160 lbs.	Boiler C. At test pressure of 320 lbs.
	Inch.	Inch.	Inch.	Inch.	Inch.	Inch.
Decrease of horizontal diameter of shell	0	$\frac{1}{32}$	0	$\frac{1}{32}$	$\frac{7}{32}$	$\frac{13}{32}$
Increase of vertical	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{3}{32}$	$\frac{5}{32}$	$\frac{3}{32}$	$\frac{1}{4}$
DECREASE OF WIDTH OF CENTRE OF COMBUSTION CHAMBER:—						
(1) At level of centre of boiler.						
Near back plate (boiler C near tube plate)	$\frac{1}{32}$	$\frac{1}{16}$	0	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{5}{32}$
At centre	0	$\frac{1}{32}$	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{3}{16}$
Near tube plate	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{1}{32}$	$\frac{1}{8}$
(2) At narrowest part.						
Near back plate (boiler C near one tube plate) ...	$\frac{3}{32}$	$\frac{3}{32}$	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{5}{32}$	$\frac{5}{16}$
At centre	$\frac{3}{32}$	$\frac{3}{16}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{7}{32}$	$\frac{1}{2}$
Near tube plate	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{32}$	$\frac{3}{32}$	$\frac{1}{8}$	$\frac{5}{16}$
(3) At springing of cylindrical part of bottom.						
Near back plate (boiler C near one tube plate) ...	0	$\frac{1}{32}$	0	0	$\frac{1}{8}$	$\frac{7}{32}$
At centre	$\frac{1}{32}$	$\frac{1}{16}$	0	$\frac{1}{32}$	$\frac{5}{32}$	$\frac{9}{32}$
Near tube plate	$\frac{1}{32}$	$\frac{3}{32}$	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{7}{32}$
DECREASE OF WIDTH OF STARBOARD CHAMBER:—						
(1) At level of centre of boiler.						
Near back plate (boiler C near one tube plate) ...	0	$\frac{1}{32}$	0	0	0	$\frac{1}{16}$
At centre	0	0	0	0	$\frac{1}{16}$	$\frac{3}{16}$
Near tube plate	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{32}$*	$\frac{1}{32}$	$\frac{3}{32}$
(2) At springing of cylindrical part of the bottom.						
Near back plate (boiler C near one tube plate) ...	0	0	0	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{8}$
At centre	0	0	0	0	$\frac{1}{16}$	$\frac{7}{32}$
Near tube plate	0	0	0	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{8}$
DECREASE OF WIDTH OF PORT CHAMBER:—						
(1) At level of centre of boiler.						
Near back plate (boiler C near one tube plate) ...	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{32}$	$\frac{1}{32}$	$\frac{3}{32}$
At centre	0	$\frac{1}{32}$	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{5}{32}$
Near tube plate	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{3}{32}$
(2) At springing of cylindrical part of bottom.						
Near back plate (boiler C near one tube plate) ...	$\frac{1}{32}$	$\frac{1}{32}$	0	0	0	$\frac{1}{32}$
At centre	0	0	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{1}{32}$	$\frac{1}{16}$
Near tube plate	$\frac{1}{32}$	$\frac{1}{32}$	$\frac{1}{16}$	$\frac{3}{32}$	$\frac{1}{32}$	$\frac{1}{16}$

* This indicates a slight return movement.

TABLE II.

	Boiler D.	Boiler E.	Boiler F.	Boiler G.	Boiler H.	Boiler I.	Boiler J.	Boiler K.	Boiler L.
Diameter of boiler (mean)	13 ft. 3 in.	12 ft. 9 in.	14 ft.	13 ft.	14 ft. 6 in.	14 ft. 8 in.	13 ft. 7 in.	13 ft.	12 ft. 6 in.
Dength of boiler	10 ft.	16 ft. 7 in.	16 ft.	17 ft.	18 ft.	17 ft.	17 ft. 3 in.	16 ft.	17 ft.
Working and test pressures	150 lbs. 300 lbs.	160 lbs. 320 lbs.	160 lbs. 320 lbs.	180 lbs. 360 lbs.	150 lbs. 300 lbs.	175 lbs. 350 lbs.	160 lbs. 320 lbs.	160 lbs. 320 lbs.	180 lbs. 360 lbs.
No. and description of furnaces in boiler	3 plain	6 Fox	6 Fox	6 Purves	6 Purves	6 Purves	6 Purves	4 Purves	4 plain, with Adamson rings
Diameter of furnace (outside)	3 ft.	3 ft. 3 in.	3 ft. $4\frac{1}{2}$ in.	3 ft. $2\frac{1}{2}$ in.	3 ft. 7 in.	3 ft. $6\frac{1}{2}$ in.	3 ft. 4 in.	3 ft. 7 in.	3 ft. 7 in.
Length of furnace, over tube plates	6 ft. 7 in.	6 ft. 8 in.	6 ft. 2 in.	7 ft.	6 ft. 2 in.	6 ft. 11 in.	6 ft. 9 in.	6 ft. $4\frac{1}{2}$ in.	6 ft. 10 in.
No. of combustion chambers in boiler	three	three, each common to two furnaces	three, each common to two furnaces	three, each common to two furnaces	six	three, each common to two furnaces	three, each common to two furnaces	two, each common to two furnaces	two, each common to two furnaces
No. of vertical rows of stays in sides of chambers	two	three	four	four	three	three	three	three	four
Thickness of shell plates	$1\frac{1}{8}$ in.	1 1-32 in.	$1\frac{1}{4}$ in.	...	1 7-32 in.	...	1 5-16 in.	1 1-32 in.	1 3-16 in.
" " chamber sides	9-16 in.	$\frac{5}{8}$ in.	$\frac{5}{8}$ in.	...	9-16 in.	19-32 in.	23-32 in.	$\frac{5}{8}$ in.	$\frac{5}{8}$ in.
" " " bottoms	$\frac{5}{8}$ in.	$\frac{3}{4}$ in.	13-16 in.	...	25-32 in.	$\frac{3}{4}$ in.	$\frac{3}{4}$ in.	13-16 in	$1\frac{1}{4}$ in.
" " furnaces	$\frac{5}{8}$ in.	7-10 in.	15-32 in.	...	15-32 in.	$\frac{3}{4}$ in.	15-32 in.	17-32 in.	$\frac{5}{8}$ in.
Chamber tops stayed by	girders	girders	girders, alternately suspended to shell	girders suspended to shell at centre of their length, and resting on tube plates at ends	curved, and gussets connecting opposite chambers	girders suspended as in boiler G.	girders	girders	girders
Chamber bottoms stayed by	not stayed	rest on brackets not secured to shell	brackets riveted to chambers and to shell	brackets riveted to chambers and to shell	stiffened by angles	⊥ bars and stays	not stayed	2 ⊥ bars	not stayed

OBSERVED ALTERATIONS OF DIMENSIONS.

	D: At Test Pressure of 300 lbs.	E: At working pressure 160 lbs.	E: At test pressure 320 lbs.	F: At working pressure 160 lbs.	F: At test pressure 320 lbs.	G: At working pressure 180 lbs.	G: At test pressure 360 lbs.	H: At test pressure of 300 lbs.	I: At test pressure of 350 lbs.	J: At test pressure of 320 lbs.	K: At working pressure 160 lbs.	K: At test pressure 320 lbs.	L: At working pressure 180 lbs.	L: At test pressure 360 lbs.
Decrease of horizontal diameter of shell	$\frac{1}{8}$ in.	$\frac{1}{8}$ in.	$\frac{1}{4}$ in.	...	$\frac{3}{8}$ in.	$\frac{1}{8}$ in.	15-64 in.	17-32 in.	...	...	3-16 in.	$\frac{1}{4}$ in.	$\frac{1}{8}$ in.	13-64 in.
Increase of vertical diameter of shell	$\frac{1}{8}$ in.	...	...	...	...	1-16 in.	3-32 in.	...	...	...	5-32 in.	9-32 in.	3-16 in.	11-32 in.
Decrease of width of centre combustion chamber at level of centre of boiler, at centre of chamber sides	3-64 in.	3-32 in.	5-32 in.	...	...	1-32 in.	5-64 in.	...	...	$\frac{1}{8}$ in.	...	...	...	...
Do. of width of side chamber at Do.	1-16 in.	...	...	...	...	3-64 in.	5-64 in.	...	...	$\frac{1}{8}$ in.	...	$\frac{1}{8}$ in.	1-16 in.	5-32 in.
Do. of centre chamber at narrowest part—Centre	$\frac{1}{8}$ in.	3-16 in.	11-32 in.	3-16 in.	9-32 in.	...	...	...	15-64 in.	$\frac{3}{8}$ in.	...	...	...	...
Near forward tube plate	...	...	...	3-32 in.	5-64 in.	...	...	...	...	5-16 in.	...	...	...	...
Near aft tube plate	...	...	...	3-32 in.	5-64 in.	...	...	...	...	$\frac{1}{4}$ in.	...	...	...	...
Do. of centre chamber at springing of cylindrical part of bottom (centre)	0	3-32 in.	5-32 in.	3-32 in.	7-32 in.	...	...	...	7-32 in.	0	...	...	...	...
Do. of side chamber at Do.—Centre	...	...	...	...	...	...	...	...	...	$\frac{1}{8}$ in.	...	$\frac{1}{8}$ in.	...	...
Near fore tube plate	...	...	...	...	...	...	...	...	...	$\frac{1}{8}$ in.	...	...	...	...
Near aft tube plate	...	...	...	...	...	...	...	...	...	$\frac{1}{8}$ in.	...	...	...	...
Increase of length of combustion chamber, fore and aft (back plate to tube plate or tube plate to tube plate)	5-64 in.	3-64 in.	5-64 in.	...	1-16 in.	1-16 in.	3-32 in.	5-64 in.	...	...	...	$\frac{1}{8}$ in.	...	1-16 in

These observations are given in Tables I. and II., and the designs of boilers to which they refer are shown in the outline diagrams, Figs. 1 to 5.

Mr. Milton remarked that "in designing boilers, the requirements of strength are generally supposed to be fully met by

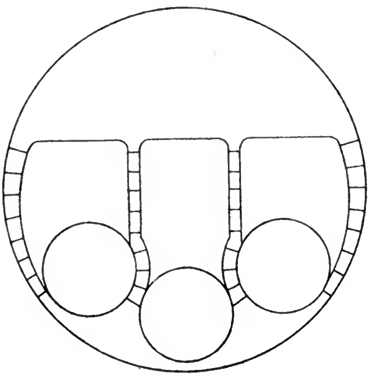


FIG. 1.

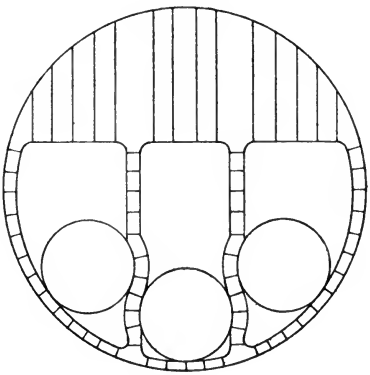


FIG. 2.

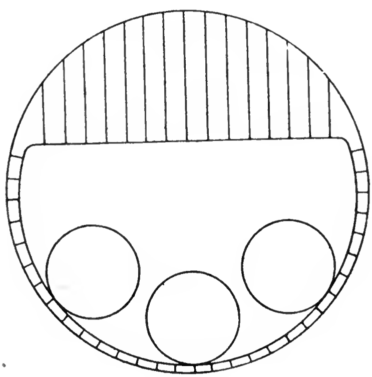


FIG. 3.

considering the cylindrical shell to be in perfect equilibrium under the uniform internal pressure, which produces a tensional stress in the shell plating proportional to the pressure and to the diameter of the boiler. The furnace flues are cylindrical in form and, together with the cylindrical portions of the combustion chamber bottoms, are supposed to be in equilibrium under the

uniform external pressure and the compressive stress it produces in the plates ; while the flat parts of the boiler are supposed to be perfectly supported by the stays. In practice, however, there are several considerations which lead to departures from the simple conditions above alluded to, and it is in consequence of these that the deformations of the different parts take place. The most important of these changes of form are the variations of the transverse dimensions of the combustion chambers, and the alteration of shape of the cylindrical shell. Considering the latter first, it is evident at once that the cylindrical shell will be in equilibrium if it is truly circular in shape, and is subjected to a uniform internal pressure, but to no other forces. If, however, it is acted upon, in addition to the pressure, by other forces not uniformly distributed round the circumference, the equilibrium will be destroyed, and an alteration from the truly cylindrical form must take place. *In most boilers these latter conditions hold.* The sides of the wing combustion chambers are stayed to the shell, as shown in Fig. 1 and unless the staying is continuous round the crown and bottom of the boiler, as in Figs. 2 and 3, the pull of the stays must distort the boiler, lessening its horizontal and increasing its vertical diameter.

" Next, consider the flat surfaces. If two equal surfaces be tied together by stays and be subjected to equal pressures in opposite directions, they will be in equilibrium, and the stress in the stays may fairly be taken as equal to the total pressure on either of the surfaces. If, however, unequal surfaces are stayed together, and are subjected to equal intensity of pressure, it is evident that, the load on the larger surface being greater than that on the smaller, the smaller surface cannot produce supporting forces in the stays sufficient to prevent all yielding, and deformation will occur, the stays moving in the direction of the larger surface, which will bulge outwards, while the smaller surface will be drawn inwards against the pressure by the stays. An illustration of this is shown in Fig. 4, which represents the horizontal section of a double-ended boiler with six furnaces and three combustion chambers. The area of the front tube plate is greater than the combined areas of the three-back tube plates. They are tied together by the tubes, and when under pressure the front tube plate bulges outwards, drawing the back tube plates with it, as shown exaggerated by the dotted lines.

"Coming to the sides of the combustion chambers, we have those nearest to the shell plates connected to the shell by stays. The pressure on the chamber side plates would cause them to bulge inwards if there were no stays; the tendency to bulge produces a tension in the stays which, as we have seen, distorts the shell from a truly cylindrical form. This yielding of the shell must be accompanied by a yielding of the chamber sides, which accordingly become curved inwards.

"If we now consider the chamber as a whole, we see that as the pressure on the side *a b* (Fig. 4) is exactly equal to that on the side *c d*, the total forces exerted by the stays on the side *c d* must also be equal to the total forces exerted by the stays on the side *a b*. The difference between the total pressure on either side and the forces exerted by the stays on that side must be borne by the tube plates *a c* and *b d*, which will be put into compression. The sides *e f* and *c d* must be under nearly the same conditions of load and support as the side *a b*, and therefore their deformation, if any, under these conditions, must practically be the same as that of *a b*, so that all three chambers will be nearly equally deformed. The stays in the water spaces are practically unaltered in length, so that the diminution of horizontal diameter of the shell will produce a collapse or narrowing of each of the chambers equal to about one-third of the alteration of diameter.

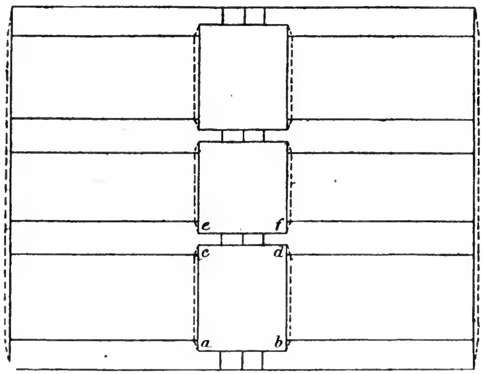


FIG. 4.

"It will be seen from the Tables that the greatest alteration

which takes place is in the horizontal width of the combustion chambers, at about the level of the centre of the wing furnaces. Fig. 5 shows a section of the boiler at this part. The wing chamber plates at about this level are parts of cylindrical surfaces, and if there were no stays fixed to them they would retain their form when the boiler was subjected to pressure. Evidently then, if, in addition to the pressure, they have forces acting on them produced by the pull of the stays, they must alter in form, yielding in the direction of the pull, the case being similar to that of the shell plating acted on by the pull of the side-stays. If any yielding takes place in this direction, the side plating of the centre chamber must become equally

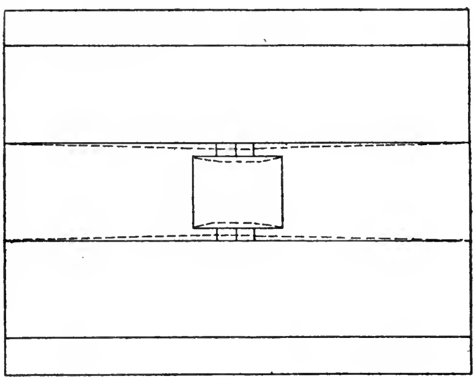


FIG. 5.

distorted, and the Tables show that in some cases the narrowing of the centre chamber produced by this distortion is nearly a quarter of an inch at the working pressure, and as much as half an inch at the testing pressure. The yielding of the wing chamber side plating is, of course, of equal amount to that of the plating of the centre chamber ; but as it is outwards at this side, while the plating at the other side yields inwards, the width of the wing chambers at this part is not so much altered, and the straining action is, therefore, somewhat masked.

"It is to be also noticed that in the side chambers, the plating being continuous at this part with the furnaces, the deformation referred to will take place without producing severe local stresses, but in the centre chamber at this level the tube plates

prevent any yielding of the side plating adjacent to them, and it scarcely needs pointing out that the deformation, being of the extent above mentioned at the centre, and nearly as much at the end stays, but practically nothing at the tube plate ends, must put a severe local strain on the plates, especially if the staying is close to the tube-plate flange."

Mr. Milton does not seem to have included in his observations any measurement of deformation of the boiler shell due to the opening made in it for the steam dome and to the form of the steam dome, or any measurement of alteration of form in the steam dome itself under pressure. Yet it is undoubted that these have been in the past serious causes of weakness, and even of danger, as explosions such as those in the steamers "Marcasite" and "Renown" long ago proved.[1]

Now, although it is to be remarked that these alterations of form which are recorded in Mr. Milton's Tables are not severe enough in general to produce a permanent set, even at the test pressures, and that in spite of the existence of such alterations many boilers, which are from their design subject to them, have continued in successful work for years, so that these deformations are not in themselves dangerous so long as boilers are constructed of material of good ductile quality, yet "their extent indicates the necessity for using material possessing a very high degree of ductility, and for so designing the details of the construction that the inevitable deformations may take place without producing severe local strains."

Oscillatory Strains—Fatigue of Metals.—It must be borne in mind also that iron and steel become deteriorated in ductility by a frequent repetition of strains which are individually much less than the stress which would produce sudden fracture or permanent set, and therefore in this view it might even be better for boilers if the test pressure produced once for all, as a permanent set, the maximum alteration of form due to the pressure.

This subject of the effect of repeated or oscillatory strains, to which the name of the "fatigue" of metals was given, was very carefully investigated several years ago by M. Wöhler, the chief Engineer of the Niederschlesisch-Märkische Eisenbahn

[1] See an article entitled "The Recent Marine Boiler Explosions," by F. J. Rowan, published in *The Anglo-Australasian*, London, 1875.

in Prussia, and in addition to M. Wöhler's papers, published in "Erkbam's Zeitschrift für Bauwesen" for 1858, 1860, 1863, 1866, and 1870, the Prussian State Railway exhibited at the Paris Exhibition in 1867 sketches of the ingenious testing machines constructed by M. Wöhler for this work, and also specimens and results of his various tests. A very interesting account of these experimental researches was given by the late Mr. Ferdinand Kohn in his book on "Iron and Steel Manufacture,"[1] and on M. Wöhler relinquishing the work, it was carried on by Prof. Spangenberg and others. Results also obtained by Sir W. Fairbairn,[2] by Prof. Knut Styffe[3] at Stockholm, by M. Josef von Stummer-Traunfels,[4] Engineer of the Northern Railway of Austria, and other investigators of the elasticity of metals, abundantly confirmed the correctness of M. Wöhler's deductions. These may be briefly stated as follows: (1) Fracture may be produced by the continual repetition of oscillating stresses, all of them much below the breaking stress. It is the differences of strain, defined by the extent of the oscillations which then produce fracture. (2). The absolute value of these stresses only enters into the question so far that the greater this value the smaller are the differences which will finally produce fracture. Short of producing fracture (though continuing up to the point of fracture) considerable changes in the molecular structure of the metal are produced by the "fatigue."[5]

Professor Spangenberg's investigations confirmed Wöhler's law, and his enquiries into the connection between the appearance of fractures and the molecular changes produced in the material broken by repeated strains, showed that the crystalline form was gradually changed to the amorphous. Thus arise

[1] Published by William Mackenzie, Glasgow, in 1869, pages 245–249. See also Min. Proc. Inst. C.E., Vols lx., 415 (containing an abstract of paper by Prof. L. Spangenberg, published in Glaser's "Annalen für Gewerbe und Bauwesen," Vol. v. p. 6), lxiii., 276–278, and lxiv. 283; *Engineering*, Vols. iv. p., 160, and xi. p., 199, etc.

[2] British Association, 1867.

[3] "The Elasticity of Iron and Steel," by Knut Styffe. London: John Murray, 1869.

[4] F. Kohn, "Iron and Steel Manufacture."

[5] "Professor Thurston's Manual of Steam Boilers" seems to be the only work on Boilers which includes this action in the consideration of the strength of boilers.

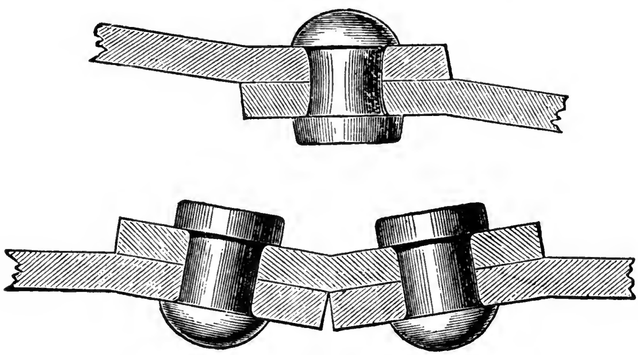
different states of equal density of the molecules, each state having its own limit of elasticity. Professor Spangenberg tested the molecular theory by means of experiments on the velocity of conduction of sound in the bars by Kundt's method, and found corroborative results.

Causes of Oscillatory Strains.—In boilers several causes combine, where deformation is possible, to produce the repetition of strains or oscillating stresses, and there are not wanting proofs of their effects on the molecular structure of the material. (1) One of these causes is the frequent raising and lowering of the steam pressure, not only at the commencement and end of a voyage or period, when steam is first got up, and when the pressure is wholly released in the boiler, but also at the various stoppages or interruptions during its course, and even in the lesser fluctuations of pressure from hour to hour, or from watch to watch, according to the state of the fires. A graphic log, such as that brought forward by Mr. Robert Caird and Mr. G. Gretchin in "The Transactions of the Institution of Engineers and Shipbuilders in Scotland" (Vol. xli., p. 155), might give a complete record of such fluctuations of pressure, but few, if any, such records have been published as yet. (2) Again, in working, the pulsatory delivery of steam to the engines has been proved to produce a gentle undulation or "breathing" action which, though small, cannot be considered insignificant on account of its frequency, being, as it is, synchronous with the number of strokes of the piston per minute.

Mr. F. A. Paget, in the paper already quoted, remarked, "According to Dr. Joule, the mere dead pressure of an elastic fluid is due to the impact of its innumerable atoms on the sides of the confining vessel. When the motion of a current of steam is suddenly checked, as by the valve, in its passage from the boiler to the cylinder, its speed and weight cause a recoil on the sides of the boiler analogous to the effects of the, in this case, almost inelastic current of water in the hydraulic ram. This action is necessarily most felt with engines in which the steam is let on suddenly, as in the Cornish and other single-acting engines, working with steam valves suddenly affording a wide outlet, and as suddenly closing. It produces such phenomena as the springing or breathing of cylinder covers, and the sudden

oscillations of gauges, noticed long ago by Mr. Josiah Parkes and others."[1] "The intensity of the instantaneous impulses thus generated would be, as Mr. Parkes observes, difficult to measure, but their repeated action must rapidly affect the boiler at its mechanically weakest points. The more or less sudden closing of a safety-valve while the steam is blowing off would evidently produce the same effect. . . . But there can be little doubt that most boilers are subjected, sooner or later, to an impulsive load."

It is well understood that the effects called "grooving" are due in the first place to such repeated actions, which not only deteriorate the molecular constitution of the metal, but otherwise



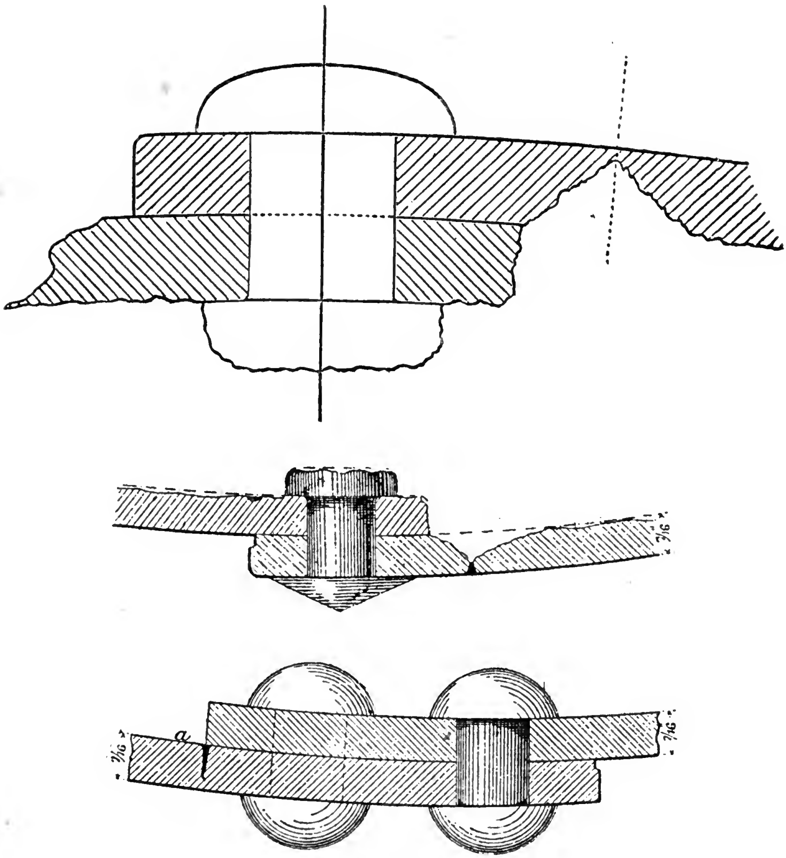
FIGS. 6 AND 7.

assist local oxidation and corrosion. Figs. 6 and 7 illustrate the forms which joints tend to assume under the influence of steam pressure in the boilers, and Figs. 8, 9, and 10 different appearances of the effects produced by grooving. Many explosions of boilers, especially those of locomotives, have been traced to this cause.

Strains due to Heating.—(3) Another source of repeated strains in boilers is found in the application of heat and in the forces produced by expansion and contraction of the material of which the boiler is constructed. In an ordinary Scotch or cylindrical marine boiler with internal furnaces, there are two portions of the boiler which are particularly exposed to considerable

[1] Min. Proc. Inst. C. E. Vol. iii.

differences of temperature in working, in consequence of which these parts have to endure the strains produced by unequal expansion. These parts are the furnace tubes and the boiler shell.



FIGS. 8, 9 AND 10.

In the case of a furnace, according to one good authority, "the portion above the fire, especially when coated with even the thin enamel of scale which is necessary to preserve it from corrosion, must be considerably hotter than the portion below the bars. Hence the top of the furnace tends to get longer than the bottom. If the end fastenings of the furnace were so rigid

as to maintain the top and bottom of the same length, the top would have to be compressed and the bottom stretched, and every difference of a degree Fahrenheit in the temperature would produce a compressive stress in the top and a tensile stress in the bottom of 93 lbs. per square inch. But, actually, the end fastenings are not so rigid, and the strains caused by the unequal expansion are not distributed from top to bottom by the ends only, but also in a great measure by the resistance to shear of the plate, and hence the greatest stresses come at the middle of the length of the furnace. Also it is evident that these strains are not uniformly distributed, and hence their maximum must be greater than their mean, and with a great difference of temperature the stresses reach a high figure. Now, by putting rings in the furnaces, the whole strain on the plate has to be borne by the reduced sectional area through the rivet holes, or at the parts which are weakened by flanging when Adamson's ring is used, and in these instances the rings have made the furnaces actually weaker than they were before, although their object is to strengthen them. In one steamship a number of the furnaces, fitted with Adamson's joints, actually tore through the bottom of the flanging the first time steam was raised. The only way to strengthen furnaces from such strains is either to prevent the difference of temperature, or else to allow the crown freedom to expand."

To prevent the differences of temperature, although it is undoubtedly the rational way, would, however, involve either a new construction of boiler or a different method of firing, and, consequently, whilst it has not hitherto been often attempted, many efforts have been made to provide for expansion of the furnace tubes. The difficulty here has been that these tubes are subject at the same time to the steam pressure, tending to collapse them, and consequently elasticity longitudinally could not be obtained at the cost of strength or stiffness circumferentially or radially. Nevertheless, the corrugated furnaces of Holmes, Fox, Farnley, Purvis, and Morison (which have successively arisen since the Bowling and Adamson joints), permit a considerable amount of expansion to take place without bringing any great stress on the furnace, but the almost incessant repetition of these temperature strains under ordinary conditions of stoking has caused even some of these furnaces in time to

crack. These incessant variations of temperature depend on the conditions of the fires, the opening and shutting of the doors, and the cleaning of the grates. "Those variations of temperature," to quote Mr. D. P. Morison,[1] "result in expansion and contraction, producing definite mechanical movements, and if the design of the furnace is such that it cannot readily adapt itself to these movements—*and no plain furnace can*—either the material becomes distressed, or such strains are produced on the boiler that leakage results. It is because of this that excessive corrosion is often found at the grate-bar level of plain furnaces."

In the case of the boiler shell, there is not the same frequency of repetition of strains, but there is no question about the magnitude of the stress produced on the plates and joints.[2] In consequence of the position occupied by the furnaces in the cylindrical boiler, the water under the level of the fire bars cannot be heated by ordinary convection currents during the process of getting up steam, and unless some special means are employed to lift it into the area of circulation it may remain practically cold for a long time. Even with special appliances some hours must be spent in gradually raising steam in order to lessen as much as possible the difference of temperature between the top and the bottom of the shell. The tops of the furnaces, stays, and tubes, and the top part of the shell are soon at or above the temperature of the steam, whilst below the furnaces the shell may have only the temperature of the feed water. As in the case of the furnaces, the top portions "tend to expand more than the bottom, bringing a compressive stress on the top portions of the boiler, and a tensile stress on the bottom. But as the sectional area of the upper portion exceeds that of the lower, so do the tensile stresses exceed in intensity the compressive ones, and the stress is so severe that it is almost universal to find the ring seams at the bottom of the boilers to be so strained as to be leaky, whilst the longitudinal seams are for the most part tight." "In several boilers (mostly double-ended ones) these stresses have been so severe as to actually fracture the plate between the rivet holes in the ring seams."

[1] "On Marine Boiler Furnaces," Trans. N.E. Coast Inst. of Engineers and Shipbuilders. January, 1893.

[2] See "On the Design and Use of Boilers," *Engineering*, Vol. xxvi., p. 284.

Force exerted by Expansion by Heat.—It is a matter of some importance to have the possible extent of such forces clearly defined. This has been done by comparing the direct effects of heat with the results produced by dynamic or mechanical means, as ascertained by those who have investigated the elasticity of metals. In Mr. D. Kirkaldy's "Experimental Enquiry into the Tensile Strength and Other Properties of Wrought Iron and Steel" (Glasgow, 1863), there is the following: "Professor Barlow states that the mean extension per ton per square inch in seven experiments on iron bars varied from ·0001082 to ·0000841, the gross mean being ·0000956. The strain, which was just sufficient to balance the elasticity of the bar, was found to vary from 11 to $8\frac{1}{4}$ tons. He remarks 'We may consider, therefore, that the elastic power of good medium iron is equal to about ten tons per inch, and that this force varies from ten to eight tons in indifferent and bad iron. It appears also (considering ·000095 as representing in round numbers $\frac{1}{10000}$) that a bar of iron is extended one ten-thousandth part of its length by every ton of direct strain per square inch of section, and consequently that its elasticity will be fully excited when stretched to the amount of one thousandth part of its length.' "

The experiments by W. H. Barlow[1] were made the basis of a comparison between the effects of heat and those of mechanical stress by Prof. W. Allen Miller,[2] who found that by raising the temperature of a bar of wrought iron of a square inch (or 25·4 mm.) in section nine degrees Centigrade, or 16·8 degrees Fahrenheit, the same elongation, viz., $\frac{1}{10000}$ of its length, was produced as was due to its being stretched when cold by a ton weight. A range of temperature of only 45° C. (or 81° F.) will cause a similar wrought iron bar, ten inches (0·254 metre) long, to vary in length five one-thousandths of an inch (or 0·127 mm.), and if under these circumstances the two extremities of the bar were securely fixed, so that elongation could not take place, that increase of temperature would produce a stress equal to about five tons per square inch.

Calculating upon Joule's data, Prof. Allen Miller remarked that it may be estimated that the force exerted by heat in producing

[1] Phil. Trans. 1855. [2] "Chemical Physics." 4th edition, p. 261.

the expansion of one pound of iron between 0° and 100° C. (32° and 212° F.), during which it would increase about $\frac{1}{280}$ of its bulk, would be adequate to lift a weight of seven tons to the height of one foot, or, in other words, would be represented by seven foot-tons.

Ordinary wrought-iron plates, it has been said, when left free from stress, expand about ·0000064 of their linear dimensions for each degree F. increase of temperature, and assuming this to be iron of ordinary ductility, of which the modulus of elasticity, according to Prof. Rankine[1] is taken at 29,000,000, a stress of 186 lbs. per square inch would produce the same elongation as one degree F. So that where a plate that is not free to move is subjected to elevation of temperature, each degree Fahrenheit increase of temperature subjects it to a compressive stress of 186 lbs. per square inch, and each degree of reduction of temperature to a tensile stress of a like amount. It may readily be understood, therefore, that serious results may be produced in boilers, portions of which are subjected to repeated strains of that nature by fluctuations of temperature.

Prof. Thurston (in "A Manual of Steam Boilers") gives the following formulæ for calculating the stress produced by change of temperature. He takes as the modulus of elasticity for good wrought iron or steel E=28,000,000 pounds per square inch, or 2,000,000 kilogrammes per square centimetre, and as the coefficient of expansion λ=0·0000068 for Fahrenheit degrees, or 0·0000120 for Centigrade degrees.

Then E=the modulus of elasticity,

λ=the change of length per degree per unit of length,

Δt^0=the difference of initial and final temperature,

p=the stress produced :—

$$p : E : : \lambda \Delta t^0 : 1$$

$$\therefore \; p = \lambda E \Delta t^0$$

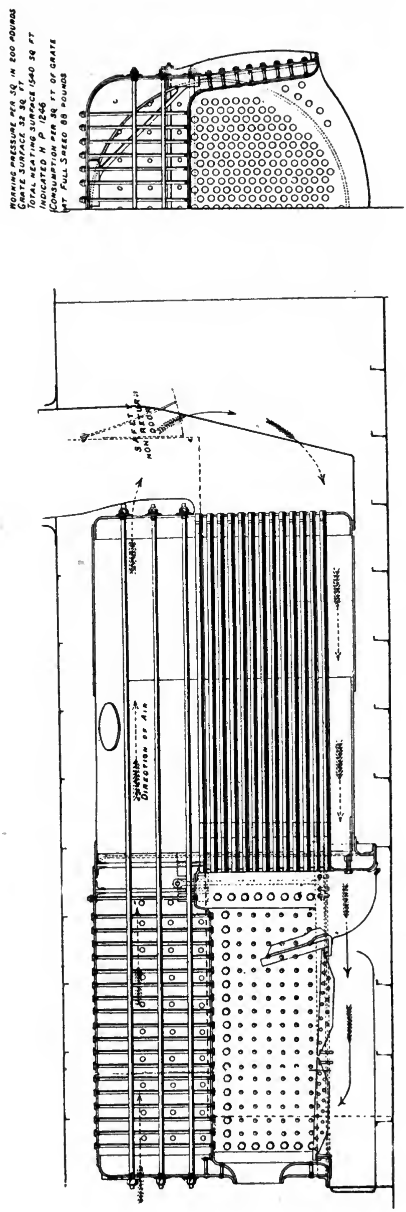
and with above values for E and λ

$$p = 190 \Delta t^0 \text{ F. nearly}$$
$$= 25 \Delta t^0 \text{ C. } \quad ,,$$

For cast-iron taking E=16,000,000, and λ=0·0000062

$$p = 100 \Delta t^0 \text{ F. nearly}$$
$$= 12 \Delta t^0 \text{ C. } \quad ,,$$

[1] "A Manual of Applied Mechanics." Second edition, p. 631.



FIGS. 11 AND 12.

Further evidence of the destructive effects of unequal heating in boilers is afforded by experiments made on this subject by Mr. A. F. Yarrow and by Dr. A. C. Kirk. The introduction of the higher temperatures of combustion which are due to the employment of mechanically produced draught, with an increased pressure of air in the stokehold or in the furnace, over that which could be obtained by chimney draught, very soon was followed by serious leaking in parts of the boilers, principally at the tube ends or joints in the tube plates.

Mr. Yarrow,[1] finding that some boilers of the locomotive or "Admiralty" pattern in torpedo boats gave trouble from tubes leaking on trial, carried out some interesting investigations. The design of boilers is shown in Figs. 11 and 12. "To ascertain exactly what

[1] "Boiler Construction, Suitable for Withstanding the Strains of Forced Draught so far as it Affects the Leakage of Boiler Tubes," by A. F. Yarrow. Trans. Inst. N.A. 1891. Vol. xxxii., p. 98.

was going on in the region of the tube plate," says Mr. Yarrow, "we removed the row of stays nearest to the tube plate flange on the sides and top of the fire-box. We replaced these stays by others working in stuffing boxes and having a nut on the outside, so that if a tensile strain had to be met they were there to receive it, while if the inside box wanted to expand it had freedom to do so. See Fig. 13. This experiment was most instructive. Every time the fire was urged these stays would all move outward through their stuffing boxes, owing to the expansion of the fire-box. In some cases the movement was sufficient to enable a penny piece to be inserted between the nut on the stay and the gland. Each time the fire-door was opened and the temperature reduced, these stays would move inward, and when the boiler was cool the nuts pressed hard on the glands. From the moment the new stays were fitted the boiler was altogether free from leaky tubes. . . . It is, of course, dangerous to draw a conclusion from one isolated

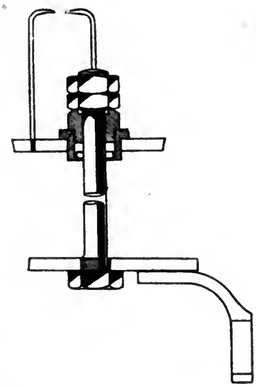


FIG. 13.

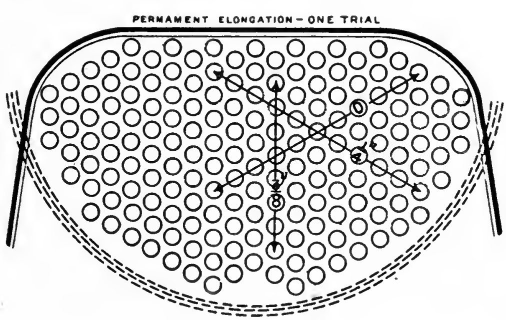


FIG. 14.

experiment. At the same time it seems more than probable that these stays, as originally fitted, had much to do with the leaking of the tubes, because it is evident that a tensile strain coming on a tube-plate weakened by being perforated

with a number of holes is likely to distort the plates. As a matter of fact, prior to the new stays being fitted, this tube plate was more or less altered in shape after every trial. Fig. 14 shows exactly the change that took place on the first trial alone. It will be seen that between the points indicated on the diagram there was in one case an extension of $\frac{1}{4}$ in., and in the other an extension of $\frac{3}{8}$ in. I think we may assume that tube plates should be free from external strains, and as far as possible be allowed freedom to move as the changes of temperature require."

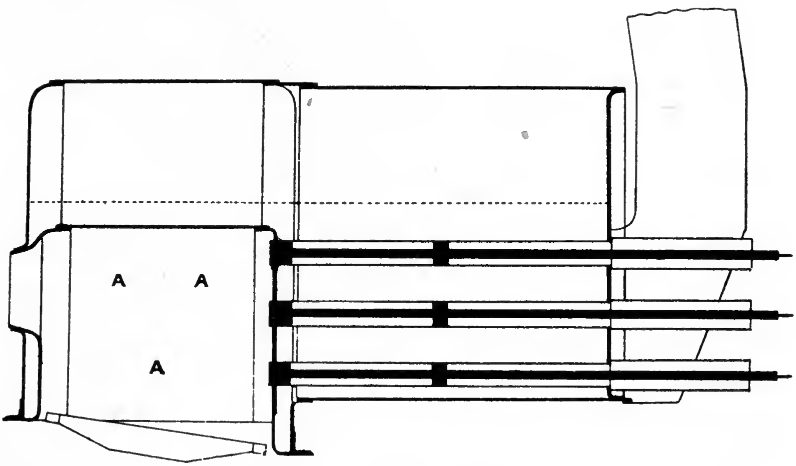


FIG. 15.

To observe the curvature of the tubes under unequal heating, during the process of raising steam and afterwards, Mr. Yarrow arranged the apparatus shown diagrammatically in Fig 15. Through three of the tubes which were at different levels were fitted bars, fixed centrally in the tube at the end next the fire and also in the middle of the tube. "The object of this experiment was to ascertain if the tubes remained straight, and, if not, to register the extent of the bending, which could be made apparent by the alteration in the position of the extreme ends of the rods. Almost immediately after lighting up it was found that the top row of the tubes was evidently heated in advance of the rest. The hotter water, as might have been expected, was near the surface, the cold water at the bottom

remained undisturbed, and the top of the boiler was also cold, owing to there being no steam to heat it. The water near the surface being raised in temperature, those tubes which passed through it strove to increase in length, but owing to the tube plates being fixed they were unable to do so, and consequently there was a considerable bending of the tubes. This was made evident by the movement of the end of the rod. After the fire had been alight about ten minutes the second bar began to move as the water at the lower level rose in temperature. In like manner, after a further interval, the third bar moved, and the bars all continued to move until such time as steam began to rise. As soon as 10 or 15 lbs. were registered the pressure on the tube plates began apparently to make itself felt, and forced them apart, throwing a tension on the tubes which straightened them. From thence up to 160 lbs. the tubes showed practically no curvature. This experiment proves how necessary it is to provide ample elasticity in the tubes, so as to conform to the conditions which have to be complied with in raising steam."

As evidence of the strains caused by unequal expansion in the boiler shell when lighting up and raising steam, Mr. Yarrow published the following Table and illustrations :—

Table III.

EXPANSION OF COPPER TUBES & OUTSIDE SHELL WHEN RAISING STEAM.
Lit up at 10.20 A.M., 4 inches over Firebox.

Time	10·30	10·40	10·50	11.0	11·10 lbs.	11.20 lbs.	11.30 lbs.	11.40 lbs.	11.50 lbs.
Steam	0	0	0	0	0-5	20-40	60-80	100-120	140-160
ELONGATION OF BARREL IN M/M. LENGTH MEASURED 3-FT. 4½-IN.=1,028 M/M.									
Boiler Shell at Water Level...	·2	·6	·8	·9	1·4	2·0	2·5	2·7	2·8
Top	0	0	0	·4	1·6	2·0	2·5	2·5	2·8
Bottom	·2	·3	·4	·8	1·6	1·6	2·5	2·5	2·5
ELONGATION OF TUBES IN M/M. LENGTH OF TUBE 3-FT. 10-IN.=1,168 M/M.									
Top Tube	1·5	1·6	1·6	1·6	2·5	2·7	2·9	3·8	4·0
Bottom Tube	·7	·9	1·5	1·4	2·0	2·5	2·9	3·6	3·6

This Table shows the longitudinal expansion of the boiler barrel at different parts, and at varying periods during steam

raising, and Fig. 16 illustrates by diagram the changes in length of another example. The movement of the inside fire-box of the boiler dealt with in the above Table is shown by Fig. 17. These examples proclaim that the distortion of form in some parts is greater during the process of steam raising than when steam has been raised. "In cooling down the strains are not so great and are quite different in character from those met with in lighting up. One main principle must be borne in mind, that any changes of temperature should take place as

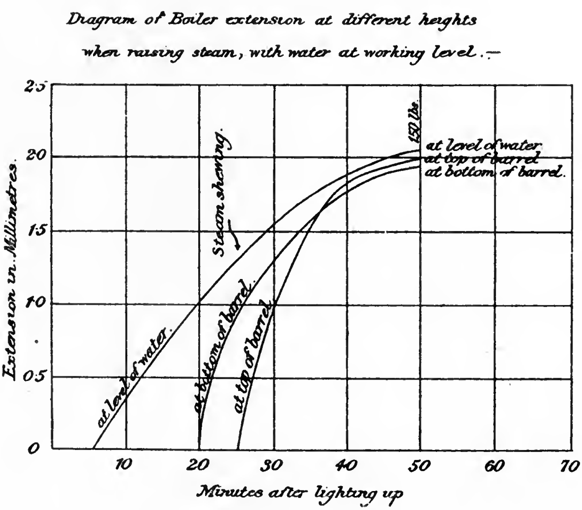


FIG. 16.

slowly as possible. The sudden putting out of the fire is therefore bad and may cause tubes to leak."

"Assuming that a tube is well expanded, it will remain tight in the plate so long as nothing takes place—such as a sudden reduction of temperature—to cause the tube to be reduced to a greater extent than the collective elasticity of the tube plate and the tube. Now, when steaming hard, if the fire-door be opened and a blast of cold air admitted, the tubes through which it passes, being thin, will feel the effect and contract before the thick tube plate. The tubes will remain tight only so long as the chilling does not tend to reduce the diameter of the tube beyond the collective elasticity of the tube and the plate.

Should this elasticity not be sufficient to make up for the change of form, the tube will leak. If the tube plate be thin, so that the rate of contraction approaches that of the tube, difficulty from this cause will be reduced. Anything that can be done to increase the range of elasticity of the tube and the tube plate, allowing thereby larger differences of temperature, is clearly desirable."

In order to test the effects of heating on tube and tube plates of different thicknesses, Mr. Yarrow had portions of plates fitted with tubes, as shown in Figs. 18 and 19,

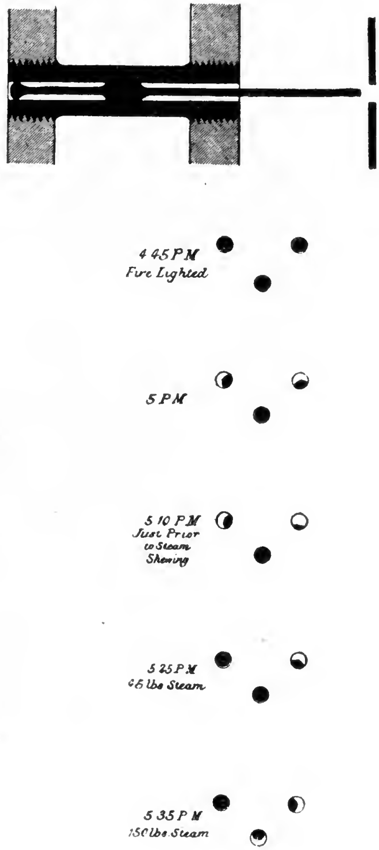


FIG. 17.

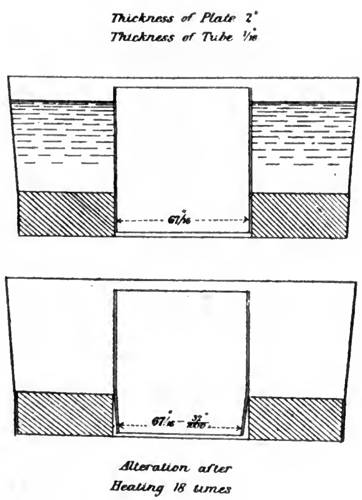


FIG. 18.

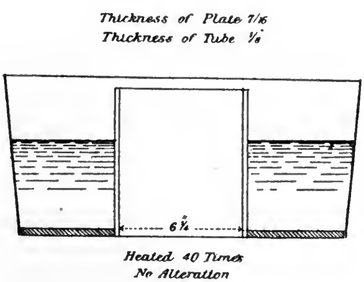


FIG. 19.

surrounded with thin sheet steel so as to form a receptacle for water, and heated over a smith's fire. Where the tube plate differed considerably in thickness from the tube, the thinner metal was necessarily heated more quickly, and its expansion due to the temperature being prevented by the cooler plate, it was gradually crushed and deformed, so that leakage soon commenced. With a more uniform thickness in both such a result was prevented.

Mr. A. C. Kirk[1] carried out a short series of experiments by means of similar apparatus, shown in Fig. 20, with the addition of fusible plugs, one of tin, one of lead, and one of antimony, which were inserted half into the tube and half into the tube

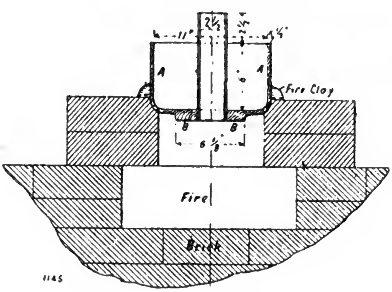


FIG. 20.

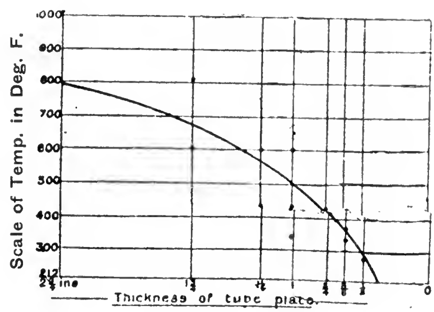


FIG. 21.

plate. The experiments were commenced with the tube plate $2\frac{3}{4}$ in. thick, with a steel tube of $2\frac{1}{2}$ in. diameter inserted in it and expanded in the usual way, the tube plate being, after each experiment, reduced in thickness by having a portion turned off its lower surface. Experiments, continuing each for half an hour or three-quarters of an hour, were made with the tube plate thickness successively $2\frac{3}{4}$ in., $1\frac{3}{4}$ in., $1\frac{1}{4}$ in., $1\frac{3}{8}$ in., a mean of $\frac{13}{16}$ in. (*i.e.*, not truly turned, having been left $\frac{3}{4}$ in. thick at one side and $\frac{15}{16}$ in. at the other), $\frac{5}{8}$ in., and finally $\frac{1}{2}$ in. The temperature to which the tube plate was raised at the fire surface was supposed to be indicated by the melting point of the metal plug or plugs which were found to have been fused in each experiment. This method, however,

[1] *Engineering*, Vol. liv., pp. 78, 333.

could give only an approximation to the real temperature, as several causes of error are possible in such circumstances, the surface of the plugs at one point being no doubt exposed to the direct heat of the fire, and therefore not necessarily registering the temperature of the iron plate or tube. Accordingly Mr. Kirk graphically represented his results in the following way, Fig. 21, drawing the curve as a mean between the highest and lowest possible temperatures as represented by the melting plugs.

The base line represents the temperature of the water when boiling, and the thicknesses of plates at each experiment are set off as abscissæ on the base line, the ordinates from these points

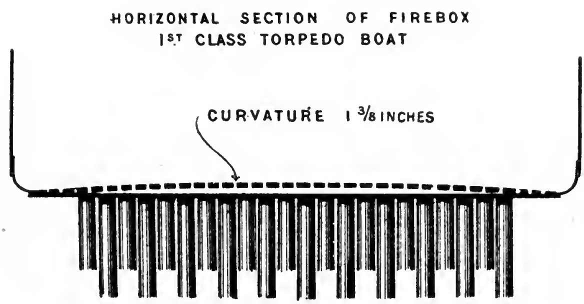


FIG. 22.

representing the temperatures of the plate at the tube end, to the scale which is given. The results of these tests simply confirmed Mr. Yarrow's conclusions as to the effects of great diversity between the thicknesses of tube and plate.

Mr. Yarrow also found that in addition to liability to deformation of tube ends by inequality of heating, there was also a tendency in the thick tube plate to assume a curved form, and in the holes through which the tubes passed to alter in form. Experiments were carried out with indicating apparatus, and Fig. 22 shows a horizontal section through the tube plate of a first-class torpedo-boat boiler, with a dotted line representing the curvature corresponding to the results indicated in the experiments where the plate was free to move. But as the plate is not free to move in a boiler, Mr. Yarrow recognised that

molecular strains are set up by the repeated variations of temperature between its two surfaces which must permanently damage the plate. "When we consider," he says, "that every time the fire door is opened and closed, the plate wants to change its form and cannot do so, and when we bear in mind that the fire door in a large forced draught boiler is frequently opened and shut, say once in every minute, which in twenty-four hours corresponds to 1,440 times, it is easy to understand that the varying expansions and contractions set up severe molecular strains, and that the tube plate is undergoing very harsh treatment."

Evidence bearing on this subject has been furnished in the experiments recorded by Mr. A. J. (now Sir John) Durston.[1] In order to ascertain the conditions to which the metal of boilers might be exposed during work, the following methods were adopted :—

1. To ascertain the temperature of the hot side of a plate through which heat is passing to boiling water, a circular flanged dish, 10 in. in diameter outside, 3 in. deep, and made of $\frac{1}{4}$-in. plate, had attached to its bottom on the fire side eight fusible plugs or buttons of different compositions, having melting points ranging between 220° F. and 250° F. This dish was half filled with water, and was exposed to the heat of a Bunsen gas flame, having a temperature of about 1500° F., over which it was allowed to remain until the water had been for some time boiling briskly. On examination it was then found that the alloys, whose melting points extended to 240° F., had melted, but that one which would fuse at 243° F. was only slightly softened, and this was held to show that the temperature of the plate at the fire side was about 240° F. A layer of grease was spread to a thickness of about $\frac{1}{32}$ of an inch over the inside surface of the bottom, and the heating repeated as before. The temperature of the outer surface of the plate was, under these circumstances, shown by the fusible alloys to have been about 330° F., or 90° F. higher than before, this increase of temperature being due to the non-conducting layer of grease.

5. With a similar vessel 24 in. in diameter, $2\frac{1}{2}$ in. deep, and of plate $\frac{1}{4}$ in. thick, placed over a forge or smithy fire and with

[1] Trans. Inst. N.A. (1893) Vol. xxxiv., p. 130.

a constant supply of water maintained during ebullition, the temperature with moderate blast was, as before, 240° F., but it increased to 280° F. with a stronger blast urging the fire. This experiment was repeated with varied conditions on the water side as follows :—

TABLE IV.

	Temperature of Hot side of Plate.	Temperature of Fire.
With clean fresh water as above	280° F.	2200° F.
" 5 per cent. American distilled oil (paraffin scale extracted) added	310° F.	2300° F.
" fresh water with $2\frac{1}{2}$ per cent. of paraffin ...	330° F.	2100° F.
" " " " " methylated spirit	300° F.	2500° F.
" grease $\frac{1}{16}$th of an inch spread on plate ...	Above 550° F.	2500° F.

2. A small experimental apparatus was constructed to ascertain the temperature, at the centre of its thickness, of a plate resembling a boiler tube plate exposed to a forced blast fire. A flanged $\frac{3}{4}$-in. plate was fitted with short lengths of steel boiler

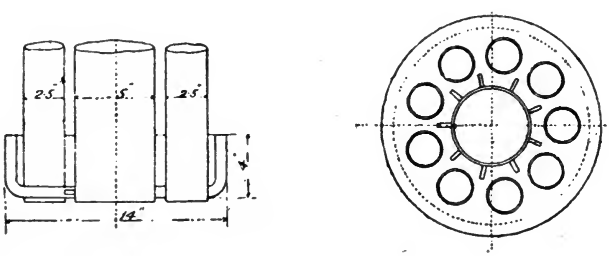


FIG. 23.

tube, as shown in Fig. 23, the centre tube being larger in order to facilitate the drilling of some holes $\frac{3}{16}$ in. diameter radially in the centre of the thickness of the plate. In these holes were placed square pieces of fusible alloys and the tubes were fixed in position by roller tube expanders as usual. Water was then

put in nearly to the depth of the flange and the apparatus was heated by a forge fire, the blast being used and the temperature of the fire being estimated at about 2000° F. The experiment was continued for about half an hour, fresh water being supplied

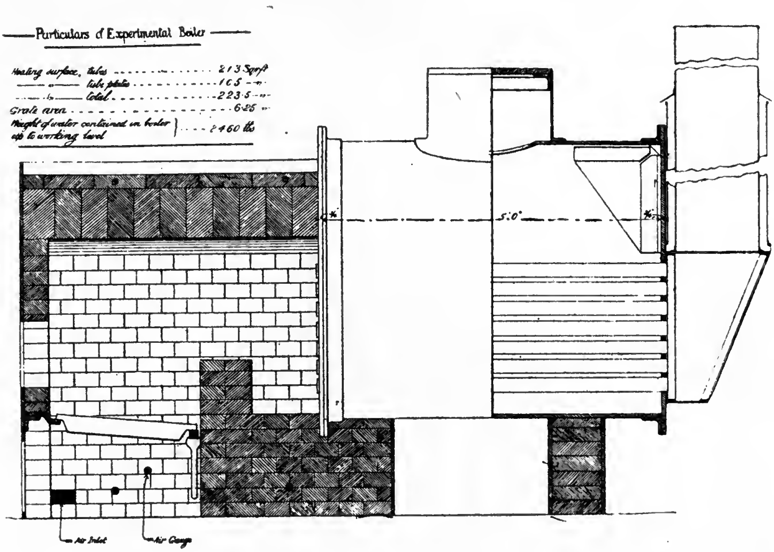


FIG. 24.

to replace the quantity evaporated. It was found that the alloys whose fusing points ran up to 290° F. had melted, but the next in order, which had a melting point of 336° F., was still

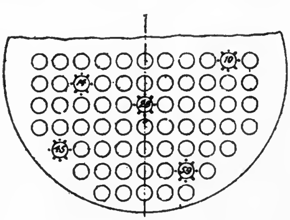


FIG. 25.

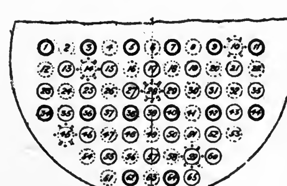


FIG. 26.

solid. The temperature of the plate at the centre was therefore taken to have been at between 290° F. and 336° F.

9. Further experiments on the temperature of the tube plate were made in an experimental boiler shown in Figs. 24, 25 and 26.

In the holes of five of the tubes, numbered 10, 14, 28, 45 and 59, as in Fig. 25, four pieces of fusible alloys, $\frac{5}{8}$ in. long, were inserted radially in the centre of the section of the tube plate, as shown to an enlarged scale in Fig. 27.

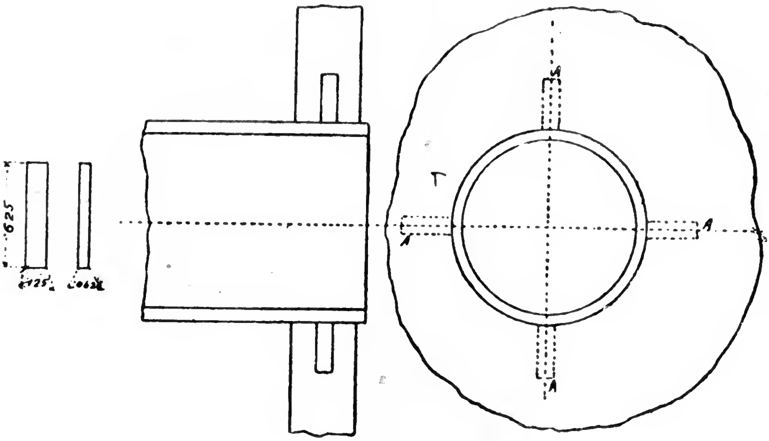


FIG. 27.

For the first experiment, which was continued for two hours the boiler had a closed ashpit with forced draught delivered into it, and the following were the conditions of the experiment :—

TABLE V.

	Mean.	Maximum.
Steam pressure	143	150
Air pressure in closed ashpit	·3″	·5″
Temperature of combustion chamber by Le Chatelier pyrometer	2850° F.	3100° F.
Temperature in tubes (middle of length)	1550° F.	1800° F.
Temperature in smoke box	1400° F.	1600° F.
Coal used per hour	188 lbs.	
" " square foot of grate	30 lbs.	
Water evaporated per hour	1039 lbs.	
" " " per square foot of tube and tube plate surface	4·62 lbs.	
Maximum temperature of steam		366° F.

The condition of the fusible alloys at the end of the experiment is shown in the following Table, from which Mr. Durston concluded that the temperature of the plate at the middle of its thickness did not rise to 540° F. but at some of the tube joints it rose to 530°F.:—

TABLE VI.

No. of Tube.	Melting Point of Alloy, Fahr.	Condition after Experiment.
59	435	Fused completely.
	450	" "
	460	" "
	470	" "
45	480	" "
	490	" "
	500	Not fused.
	540	" "
10	510	" "
	520	Fused at end next tube.
	530	" " "
	540	Not fused.
28	550	" "
	617	" "
	680	" "
	773	" "
14	550	" '
	617	" "
	680	" "
	773	" "

10. For some subsequent experiments the boiler was enclosed in an air-tight stokehold and the draught was supplied by a more powerful engine and fan in order to obtain a higher rate of combustion. In addition to the fusible alloys in the middle of the section of the plate, four pieces, each $\frac{5}{32}$ in. in length, and $\frac{3}{16}$ in. in diameter, were fitted into the face of the plate around each of the numbered tubes, as shown in Fig. 28. These pieces projected $\frac{1}{32}$ in. beyond the face of the plate, and

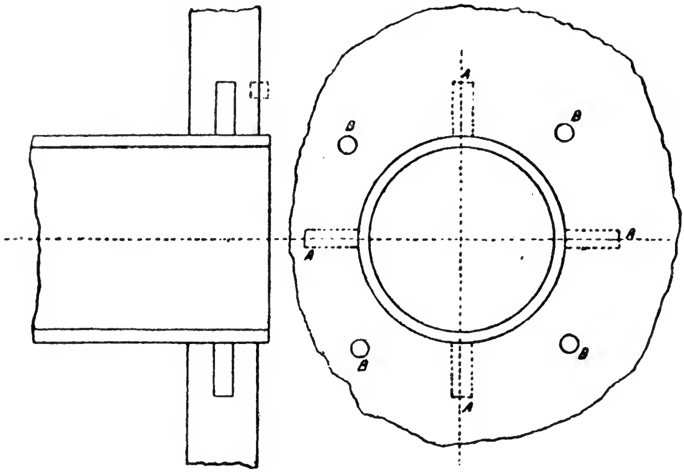


FIG. 28.

were of different materials in four different trials. The following are the data of the trials :—

TABLE VII.

Trials.	1st.	2nd.	3rd.	4th.
Duration of trial ... hours.	5	5	5	$3\frac{5}{6}$
Pressure of steam ... ... lbs.	145	142	140	144
Air pressure in stokehold ins.	3	3 for 2 hrs. $3\frac{1}{2}$ for next 3 hrs.	3	2·9
Total coal used during trial lbs.	2800	3188	2632	not accurately taken
Total water evaporated ... lbs.	14125	14775	13148	10276
Coal per sq. ft. of grate per hour ... ... lbs.	90	102	84·2	
Water evaporated per sq. ft. tube and tube plate surface per hour ... lbs.	12·64	13·22	11·76	11·99
Temperature in combustion chamber ... ... F.	2750	2500	3100	3200
Amount of mineral oil used ... ... lbs.			9	5
Oil used in percentage of fuel			·07	·05

On the first trial, with clean feed water, 16 of the pellets on the face of the plate were made with melting points from 490° to 690° F. and the remaining four were of antimony (melting point 1060° F.) All were melted except the four antimony.

On the second trial, also with clean feed water, the pellets placed in the face of the plate around each of the five tubes were one of antimony (1060°), two of zinc (750°) and one of an alloy melting at 690°, arranged as in Fig. 29. Of these the five antimony and three of the zinc at tubes 14, 45 and 59 remained intact, whilst all the rest melted.

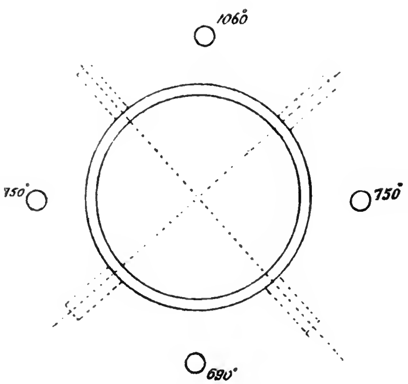


FIG. 29.

On the third trial, with pellets arranged as in the preceding trial, 9 lbs. of oil were fed into the boiler with the feed water. The five antimony and one zinc pellet (at tube 45) out of the pellets remained intact, but all the rest melted.

On the fourth trial, the boiler not having been cleaned out after the preceding trial, an additional 5 lbs. of oil was admitted with the feed water. During this trial the tubes gave out when cleaning fires after $3\frac{5}{8}$ hours working. Around tubes 10, 14 and 28 (the hottest part of the plate) all the zinc and alloys melted; the antimony partly melted in Nos. 14 and 28, but remained intact at No. 10. Around tubes 45 and 59 the antimony and zinc remained intact. This showed that the plate was presumably about the temperature of 1060° F., at all events during the latter part of the trial, when it is supposed the tubes gave out, whereas in the former trial they remained tight up to and above the temperature of melting zinc (750°F.).

The five tubes were then drawn, in order to examine the fusible plugs let into the plate radially. These had been arranged as in Fig. 30.

All were found melted except the zinc at tubes 14 and 28.

At tubes 14 and 28 the temperature at the face of plate is held

to have been 1060° F, and at the middle of plate between 680° and 750°F.

Commenting on these experiments Mr. Zittenberg[1] (of Nagy-Kanizsa, Hungary) made the following observations as to the stress at the tube ends :—

"A tube internally heated and externally cooled, under an assumed temperature T on the fire side, t on the water side, and expanded diametrically according to a temperature θ, between t and T, is under compression on the fire side, conforming to the difference $T-\theta$, and under tension on the water side conforming to $\theta-t$. For every degree Centigrade, steel suffers a stress of 320 lbs. per square inch and copper 270 lbs. per square inch. Taking the difference between mean and firebox temperatures proportionally to the thickness of the plates, you would find according to the 10 experiments 33° C. difference

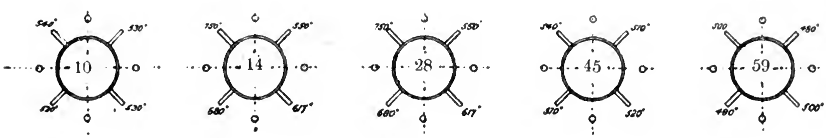


FIG. 30.

between mean and hottest temperatures of tube, compressing it to 10,000 lbs. per square inch. Experiment No. 9 showed that the fusion pellets indicated the exterior of the tube plate to be between 252° C. and 257° C., while pellets of 268° C. and 273° C. melting point fused only at the end near the tube. This indicates an excess of the temperature of the tube over the mean of the plate of at least 15° C., giving at least 5,000 lbs. per square inch further compression. If you consider that the tube is also highly compressed by the act of expanding, the difference of temperature between tube and outer shell of the tube plate, which can expand only according to its mean temperature and not according to the extreme, you will agree that the sum of these stresses comes near the elastic limit and transcends it when the material softens at higher temperatures and tends to localise the effects which, otherwise, are partly expended on the body of the tube.

[1] See *Engineering*, Vol. lv., p. 440.

"If we add to all this the difference of expansion and elastic strength, we understand why tubes of copper and brass do not do well in tube plates of steel, as also steel tubes in the copper plates of locomotive boilers where hard water deposits a thick scale. . . .

"The same holds good for the ingress of cold air, which does very little harm to the locomotive tubes in the Tyrol, with its extremely soft water, but produces instantaneous leaking in part of Hungary, with its very hard water."

It is manifest that most water-tube boilers are not subject to the strains which produce distortion of tube plates of considerable extent, and that, consequently, they are not so liable to suffer from leaking at the joints. No doubt a great stress is thrown upon thin tube joints, but to resist pressure these probably have an ample margin of safety. Mr. Yarrow has stated that a 2-inch steel tube expanded by a roller expander in a steel tube plate has a holding power of 8 to 12 tons against stress. In the firebox of a boiler of locomotive pattern, with 200 lbs. pressure of steam per square inch in the boiler, the total strain tending to separate the two tube plates is equal to 124 tons, whilst the total holding power of the tubes at 8 tons per tube was found to be 2,300 tons, giving a margin of safety of nearly 20. The tubes of water-tube boilers have the advantage of the steam pressure being within them, as this tends to strengthen their hold on the plates or chambers into which they are expanded and to prevent leaking at their joints.

It must not be supposed, however, that water-tube boilers are wholly exempt from oscillatory strains, or that, if not well designed and worked with regard to them and to the other actions proceeding during the use of such boilers, they will not suffer also. Their larger margin of strength will, no doubt, cause them to suffer less in some ways, but their thinner material will sooner cause any destructive action to become apparent. The observations and remarks on the action of the boilers of the T.S.S. "Kherson," published by Mr. G. Gretchin,[1] Engineering Superintendent of the Russian Volunteer Fleet, furnish us with some useful information on this point. A full description of the machinery of this vessel was published

[1] Trans. Inst. Engineers and Shipbuilders in Scotland. Vol. xli., page 299. (1898).

in *Engineering* of 6th December, 1896, and a graphic log of part of her run from St. Petersburg to Vladivostock, and from Vladivostock to Odessa, is printed in the "Transactions of the Institution of Engineers and Shipbuilders in Scotland." (Vol. xli.)

There are in this vessel 24 Belleville boilers, placed back to back athwartship, in three separate groups of eight boilers each. The boilers have each eight elements, consisting of 20 lap-welded iron tubes of $4\frac{1}{2}$ in. outside diameter, the two lower tubes of each element being $\frac{3}{8}$ in. thick, the two next $\frac{5}{16}$ in. thick, and the rest $\frac{1}{4}$ in. thick. The connecting boxes are of cast steel. The total amount of heating surface is 35,350 square feet, and the grate surface 1,132 square feet.

On the occasion of the first mooring trials in February, 1896, the middle group of boilers was under steam, the conditions of working being identical for the boilers on the starboard side and those on the port side, except that it was found at the end of the trial that the ship had a list to starboard of $10\frac{1}{2}$ degrees. The boilers on the starboard side worked well, but leakage took place in the joints of the bottom boxes with the feed collectors in all the port boilers, and after the trial it was found that nearly all the tubes of these boilers were bent downwards, 13 of them being out of line from 1 in. to $1\frac{1}{2}$ in. On the next trial the list was five degrees to the other side, and a similar result followed, to a less degree, in the tubes of the starboard boilers. "This coincidence of the list of the ship and the irregularity of working of the boilers on one side was observed afterwards," Mr. Gretchin remarks, "during the whole round voyage." Each time there was a list leakage was found in the feed collector orifices on the side opposite, and the feed pumps on that side also worked irregularly. "The examination of the tubes, which was made each time the boilers were stopped, showed the bend of the tubes to be downwards on the opposite side from that to which the ship was listed, and what was of greater interest, the tubes on the other side, which were bent before, had a tendency to become straight, and some of them even got bent upwards. As a rule, the lower tubes of Belleville boilers tend to bend upwards if the boilers are working in their normal condition."

Mr. Gretchin had previously observed this latter phenomenon in the boilers of the French steamer, "Ville de la Ciotat," on

a voyage from Marseilles to Port Said. He explains the correspondence of the bending of the tubes and the list of the ship as follows: "Supposing the list is on the starboard side, the first, third, and all the uneven tubes of the elements of the port boilers will be horizontal if the list is equal to $2\frac{1}{2}$ degrees; and the back ends of these tubes will be higher than the front ends when the list is greater than that." This is illustrated in Fig. 31, showing the normal position of the tubes, and Fig. 32 that due to a list greater than $2\frac{1}{2}$ degrees. "In this case the steam generated in the first lowest tube, which is directly connected with the feed collector, will go, or have a tendency to go, to the feed collector. It is possible that under certain conditions the power of motion of the steam bubbles in this direction is greater than the force which produces circulation.

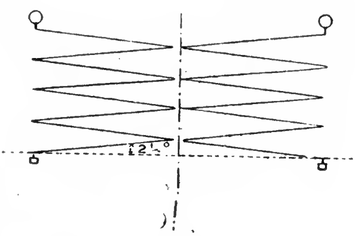


FIG. 31.

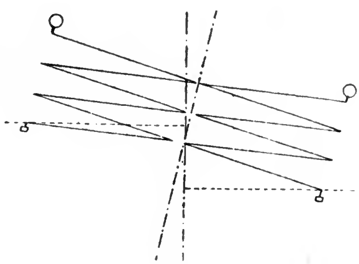


FIG. 32.

At the moment this comes into action the water supply will be checked, the tube overheated and liable to be bent downwards. . . . If this return motion of the bubbles takes place, and if the tubes get bent, as experience proves, it is quite possible that these two phenomena may occur at the same moment. When the tube is bending, the female cone of the bottom connecting-box moves on the male cone of the feed-collector, and the result is leakage through the joint. This supposition is proved by the fact that the leakage was always much worse in the boilers which were working under conditions unfavourable as regards circulation of water."

After a voyage from Newcastle to St. Petersburg, the tubes were examined outside and measured. The results of measurement of the two lowest tubes, which were nearest the fire, are given in the following Table, in which the top row of figures

refers to the different elements of each boiler, and the first column of figures denotes the individual boilers whose tubes are thus dealt with. The measurements of the same tubes as taken at Newcastle before the voyage are inserted in each case for comparison. The figures without arrows represent the extent of downward bending, and those with arrows indicate upward bending.

TABLE VIII.

	Number of Boilers	Port where tubes were examd.	Tube	I	II	III	IV	V	VI	VII	VIII
Port Side	18	Newcastle	Sec	1/8	1/16	1/4	1/8	0	1/16	1/8	3/16
			First	↑ 3/16	3/8	1/4	1/4	3/16	1/8	3/16	5/16
		St Petersburg	Sec	↑ 1/16	1/16	0	3/16	1/8	0	0	0
			First	1/2	3/16	3/16	3/8	1/2	1/2	3/16	3/16
	20	Newcastle	Sec	1/8	1/8	1/8	1/8	1/8	0	1/8	1/8
			First	1/4	1/4	3/16	3/8	3/16	1/16	1/8	1/8
		St Petersburg	Sec	0	0	0	1/16	0	0	0	0
			First	5/16	1/2	1/2	3/4	1/2	3/16	3/8	1/4
	22	Newcastle	Sec	1/16	1/8	3/16	1/8	1/8	1/4	0	0
			First	1/8	3/8	3/8	1/4	1/4	1/4	3/16	1/16
		St Petersburg	Sec	0	1/8	3/16	1/8	1/16	1/8	1/8	0
			First	5/16	3/8	1/2	5/16	3/4	9/16	3/8	3/8
	24	Newcastle	Sec	3/16	1/16	1/8	0	0	1/16	1/16	0
			First	1/16	1/8	1/4	1/8	3/16	1/4	0	1/4
		St Petersburg	Sec	1/8	1/8	3/8	1/16	0	1/16	0	0
			First	1/2	1/2	1/2	5/8	5/8	3/4	3/8	1/16
Starboard Side	23	Newcastle	Sec	1/16	1/16	3/16	1/8	1/16	0	1/8	1/8
			First	1/8	1/8	1/8	3/16	1/8	0	3/8	3/8
		St Petersburg	Sec	1/8	1/16	1/4	1/8	1/8	3/32	1/4	3/16
			First	1/16	1/32	0	0	1/32	0	0	↑ 1/32
	21	Newcastle	Sec	1/8	1/16	↑ 3/16	1/8	1/8	1/4	1/16	1/8
			First	1/16	1/16	1/16 *	5/16	3/8	3/8	1/4	3/16
		St Petersburg	Sec	1/4	1/8	↑ 5/16	1/8	1/4	3/16	1/16	1/16
			First	3/8	1/8	↑ 1/16	↑ 1/16	1/8	↑ 1/8	0	0
	19	Newcastle	Sec	1/16	1/8	1/8	0	1/8	3/16	1/8	3/16
			First	3/8	3/8	5/16	1/4	5/16	7/16	9/16	1/2
		St Petersburg	Sec	1/16	0	0	↑ 1/32	1/16	3/16	1/16	1/16
			First	3/8	1/2	3/16	0	3/16	3/8	1/2	3/8
	17	Newcastle	Sec	1/16	1/8	1/8	1/8	3/16	1/8	0	1/8
			First	0	5/16	7/16	5/8	1/2	9/16	1/4	1/8
		St Petersburg	Sec	0	1/8	3/8	1/16	1/8	1/8	1/8	1/8
			First	1/16	5/16	1/2	5/8	[illegible]	1/2	1/4	5/16

* [illegible]

"It can be seen from the Table that nearly all the tubes of the port boilers were bent downwards, and three of them as much as $\frac{3}{4}$ in. In the second row of tubes, which was at a greater inclination when the list was to the starboard side, the bends decreased, and many of the tubes returned to their original form. The change of form of the tubes on the starboard side was not so considerable as on the port side; nevertheless in 23 out of 32 tubes the bend had decreased. Six of these 23 became quite straight, and four tubes even got bent upwards.

"About three-quarters of the whole number of tubes were out of their original straight form when the 'Kherson' returned home. . . . In some cases the tubes were bent upwards, but on every occasion the bend was in accordance with the list of the ship when the boilers were under steam. The largest number of tubes were bent about $\frac{3}{8}$ in. in the middle, the smaller number only $\frac{1}{8}$ in., but a few as much as $1\frac{1}{8}$ in."

There is no doubt that the special design of the Belleville boilers—that of a flattened spiral—renders it specially liable to differences of temperature in the tubes. All the steam formed in each tube has to be conveyed by that tube, which is more or less inclined to the horizontal, so that the steam must pass along the upper side of the tube. This leaves a steam space in contact with the top side of the tubes of all boilers constructed with nearly horizontal tubes, and as the under sides of the same tubes are in contact with water, there may be a considerable difference in temperature between the two sides. In the Belleville boiler, however, this result is increased proportionately in the tubes above the lowest row, because each horizontal tube in the spiral has to convey, not only its own steam, but also all that is formed in the tubes below it. In the topmost rows, before the steam chamber or drum is reached, as a consequence, there may be nothing but steam, or only a little water broken up into froth, and these tubes may readily attain a temperature considerably higher than those of the lowest rows, where there must be a considerable quantity of water present while the boiler is at work. All these opportunities for differences of temperature point to possible strains which had much better be avoided.

"Every design," remarked Mr. Yarrow at the close of his paper, "is more or less a compromise, but the investigation

which we have made points to the importance of leaving nothing undone to ensure a design conforming to the requirements of changes of form due to changes of temperature. It also points to the importance of adopting only the highest classes of material, so as to ensure ample elasticity to help in conforming to these changes, some of which are considerable."

After such an object-lesson, it is clear that we can with confidence formulate certain axiomatic statements of the requirements of boiler design.

1. Strength should be the maximum for the pressure, and should be due to form, not to thickness of material, or artificial strengthening by stays.

2. Weight should be the minimum per unit of power, consistent with strength. This is true, not only for marine boilers, because useless weight means useless material and unnecessary strains upon structure and supports.

3. The design should provide for facility of construction and repair.

4. The form must be regulated by the requirements of the circulation of the water and of the heating medium.

5. The heating surface should be the maximum consistent with other requirements.

The first three of these really follow from what has been before us in this chapter; the evidence for the last two we have still to consider, although the "Kherson's" boilers afford some illustration of No. 4.

CHAPTER III.

COMBUSTION.

COMBUSTION is necessarily the first action which takes place in the process of steam generation, and in this process the problem which is presented to us is a two-fold one, viz.: First, how to obtain the maximum amount of heat from the fuel which is employed, and second, how to transmit the maximum amount of that heat to the water. The first portion of this problem is what concerns us here, and the first step in it is to ascertain what is the maximum amount of heat derivable from the fuel. The main facts of the chemistry of combustion have been repeatedly set forth in text books, and to-day may be said to form a portion of the alphabet of engineering knowledge. Yet we find in this, as in other departments of our subject, that there is abundant room for further research and improvement, or advance in knowledge.

Calorific Value of Fuel.—The ultimate constitution of fuels, or the proportions of the various elementary bodies into which they are resolved by the processes which are employed therein, can be learned from ordinary chemical analysis. In statements of analysis of coal, we have usually given to us the percentage proportions of carbon and hydrogen into which the coal has been resolved by the action of heat, and these are used in calculations of the calorific power of the fuel as represented by the units of heat yielded by the combination of these elements with oxygen.

But the sum of the substances into which coal or other fuel can be resolved by the heat or other actions employed in a chemical analysis, tells us very little about the *proximate* composition of the fuel analysed. And, speaking generally, the temperature to which the small sample of say, coal, is subjected during the course of an analysis may produce effects which are somewhat divergent from those which are produced when the same coal is subjected to very different conditions in actual use. Coal does not consist of carbon merely mixed with hydrogen, but is composed for the most part of solid hydrocarbons, the formation of which from woody fibre by successive

dehydrations is well understood by chemists, who have termed this process "cumulative resolution."[1] Very little has, however, been done towards separating these various hydrocarbons in their natural state from coal, and showing in what manner they are grouped or held together in that substance. A very excellent commencement of such investigations is, however, described in "A Contribution to the Chemistry of Coal, etc.," by W. Carrick Anderson, M.A., B.Sc., Assistant to the Professor of Chemistry, Glasgow University. (See Proc. of the Philosophical Society of Glasgow, Vol. xxix., pp. 72-96.) From this research, it seems to be probable that the different varieties in the quality and composition of coal (such as anthracite, gas coal, splint coal, coking coal, soft coal, etc.), are due to degrees of oxidation of the coaly matter when "resolved" from woody fibre. When heat is applied to coal, gaseous hydrocarbons of varying composition are formed by reactions taking place in the substance of the coal itself, and are evolved from it; a certain quantity of what is called "fixed carbon" or "coke," but which should be called "deposited carbon,"[2] remaining after all the gaseous hydrocarbons have been driven off.

The following Table exhibits the differences between the calorific powers and specific heats of five known varieties of pure solid carbon, as found by Favre and Silbermann,[3] who deduced from them the conclusion that there is no exact relation between the calorific power and the specific heat of carbon in the different allotropic states.

TABLE IX.

Variety of pure Carbon.	Calorific Power.	Specific Heat (Regnault).
Wood charcoal	8080	0·24150
Gas retort carbon	8047·3	0·20360
Artificial graphite	7762·3	0·19702
Native graphite	7796·6	0·20187
Diamond	7770·1	0·14687

[1] On "Cumulative Resolution," by Prof. E. J. Mills, D.Sc., F.R.S.

[2] See "On Fuel and its Applications," by E. J. Mills, D.Sc., and F. J. Rowan. Vol. i. of Groves and Thorp's Chemical Technology. London, 1889.

[3] See Percy's "Metallurgy," Fuel, p. 163.

These facts have also suggested the conclusion that the heat of combustion of an elementary substance depends not only upon its chemical constitution, but also upon its physical state before combustion.[1] Favre and Silbermann also noticed that the density of both simple and compound bodies exerts an influence upon their calorific value, and that the fuel value of polymeric bodies varies with the state of condensation of their molecules, with which it is in inverse ratio. As an illustration of the differences existing in simple bodies in different allotropic conditions, they instanced carbon vapour, whose fuel value they reckoned at 11,214 calories, natural graphite they valued at 7796·6, and diamond at 7770 calories.

The fuel value of the "fixed carbon," "coke," or "deposited carbon," into which a portion of coal is resolved depends, therefore, upon its density, which is largely determined by the temperature and pressure at which its formation has taken place.

With regard, also, to the hydrocarbons which are formed by the action of heat on coal, their composition depends upon the temperature to which the coal has been exposed during distillation or decomposition, and since the calorific value of the different hydrocarbons varies with their constitution and that of solid carbon with its physical state, it is evidently not easy to find an exact relation between the results yielded by any given coal on analysis and those found in actual use. Even with different methods of use different results are obtained. In connection with this subject, another consideration deserves some attention. In the calculation of the calorific value of fuels, it is always assumed that all the carbon of the fuel exists in it as solid carbon and has the value of wood charcoal burning to carbon dioxide, whilst all estimations of the calorific power of hydrogen are made with it in the state of gas. In neither case does this truly represent the actual condition of the fuel.

In the case of coal, a considerable portion of the carbon must burn in the state of gas along with the hydrogen, both elements having been previously united in a solid form. In the case of liquid fuel, none of the carbon or hydrogen exists in a solid form,

[1] See "Coal, its History and Uses," by Prof. Rücker, p. 243. London Macmillan, 1878.

and both substances must be wholly consumed in the state of gas, if that kind of fuel is to be economically used.

An illustration of the nature of the discrepancies which may, and undoubtedly often do, exist between the heat values, as calculated from elementary composition and as found in actual use, is afforded by a comparison of marsh gas with acetylene. Marsh gas is represented by CH_4, but it has been found that 16 grams of marsh gas give out in burning less heat than do the 12 grams of carbon and 4 grams of hydrogen gas of which it is composed. It is readily decomposed by heat into its elements, and is generally formed by actions taking place at a low temperature. Acetylene (C_2H_2), on the other hand, has a higher heat value than is shown by the sum of its elements, as 26 grams of C_2H_2 give more heat than do 24 grams of carbon and 2 grams of hydrogen gas. Unlike marsh gas, acetylene is produced by reactions taking place at a high temperature, and this may account for its greater potential energy. One of the fundamental principles of thermo-chemistry is that the quantity of heat evolved is the measure of the sum of the chemical and physical work accomplished in the reaction. This, of course, supposes that all the actions taking place in the accomplishment of a given result are known, so that the elements of which that result is composed can be counted. When, for instance, solid bodies become by chemical union a gaseous compound, heat is absorbed or becomes latent,[1] and a portion of this heat may become sensible during the transfer of one of these gaseous constituents to another combination. With regard to coal, however, it cannot be pretended that we know all the reactions taking place during its combustion, or the full effect of conducting that combustion at various temperatures. In general, the theoretical thermic values of the different elements calculated as burned in oxygen are taken as the basis of calculation of the heat value of fuels, with some small deductions due to the presence of oxygen in the fuel, to the employment of atmospheric air, and to the specific heat of the products of combustion.

The following Table shows these theoretical calorific values of the principal substances found in coal and other fuel.

[1] See "On the Physical Conditions Existing in Shale-distilling Retorts," by F. J. Rowan, Jour. Soc. Chem. Industry, Vol. x., 1891.

TABLE X.

	Symbol and atomic weight.		Heat evolved by the combustion of 1 lb. of substance.	
	Before combustion.	After combustion.	British thermal units (lb.F. degrees)	lbs. of water evaporated from and at 212°.
Hydrogen burned in oxygen ...	H 1	H_2O 18	62,032	64·21
Carbon burned in oxygen to CO	C 12	CO 28	4,451	4·61
Carbon burned in oxygen to CO_2	C 12	CO_2 44	14,544	15·06
Carbonic oxide burned in oxygen CO_2	CO 28	CO_2 44	4,326	4·48
Olefiant gas (ethylene) ...	C_2H_4 28	$\left\{\begin{matrix} 2CO_2 \\ 2H_2O \end{matrix}\right\}$ 124	21,343	22·09
Marsh gas (methane) ...	CH_4 16	$\left\{\begin{matrix} CO_2 \\ 2H_2O \end{matrix}\right\}$ 80	23,513	24·34

With regard to the oxygen in the fuel, as it exists for the most part in moisture, hygroscopic or free, and is therefore useless for combustion, being already combined with its equivalent of hydrogen, it is usual to deduct from the hydrogen one-eighth of the weight of the oxygen. The remainder of the hydrogen is called the "disposable hydrogen," and in calculations of calorific power is generally reduced to the heat-producing equivalent of carbon. The general statement of the calculation for calorific value is therefore :—

$$\text{Calorific value} = 14{,}544\left\{C + 4{\cdot}265\left(H - \frac{O}{8}\right)\right\}$$

For the quantity of water which the fuel can evaporate from and at 212° Faht. (966 British heat units being required per lb. of water evaporated), the following is used :—

$$\text{lbs. of water evaporated} = 15{\cdot}06\left\{C + 4{\cdot}265\left(H - \frac{O}{8}\right)\right\}$$

In some books the round numbers 62,000 for hydrogen, and 14,500 for carbon, are adopted in calculating heat values of fuel, and this causes a slight alteration in the figures given above.

Thus D. K. Clark[1] gives the following formula for heating power :—

$$h = 145\ (C + 4{\cdot}28\ H)$$

[1] "The Steam Engine," Vol. i., p. 38.

and for evaporative power :—

$$\text{(with water supplied at } 62^\circ) \; e = 0{\cdot}13 \, (C + 4{\cdot}28 \, H)$$
$$\text{(with water supplied at } 212^\circ) \; e = 0{\cdot}15 \, (C + 4{\cdot}28 \, H)$$

These calculations afford approximate estimates (apart from the effects of the products of combustion) of the value of fuels for steam raising, but it is well known that they are certain to give results which are short of what can be realised with fuel properly used.

Efforts have not been wanting to improve the basis of such calculations, so that their result should come nearer to the possible with fuel in actual use. One of the best attempts hitherto was made by M. Cornut,[1] chief engineer to the Northern (of France) Steam Users' Association, who suggested the formula (expressed in calories) :—

$$Q = 8080C + 11214C^1 + 34462H.$$

when Q = the total quantity of heat,
C = the fixed or solid carbon, and
C^1 = the volatile carbon contained in the coal.

The uncertain factor in this case, however, is the value ascribed to the gaseous carbon, because, as we have seen, all hydrocarbons have not the same calorific value, which depends, no doubt, to a great extent on the temperature of their formation.

In the case of liquid fuel, Harrison Aydon[2] proposed to give all the carbon contained in it the heat value of 21,600 British heat units (that is, practically the same value as M. Cornut employed in calories), which Prof. Rankine had stated was the number due to gaseous carbon. A small expenditure of heat, however, suffices to gasify the whole of the oil of most qualities which are used for fuel, and when this preliminary gasification is properly carried out the resulting gas has usually a much higher calorific power than is represented by the constituents of the oil itself[3] as analysed. It seems to be quite possible to improve the methods of analysing fuels, with a view to the report

[1] "Etudes sur la Combustion de la Houille," from Bulletin de la Société Industrielle de Mulhouse. Paris, 1875.

[2] Min. Proc. Inst. C.E., Vol. lii.

[3] See "On the Calorific Value of Solid and Liquid Fuels," by F. J. Rowan, Jour. Soc. Chem. Industry, Vol. vii., p. 195.

of analysis giving a better conception of their calorific value, and the author of this work has suggested (in "Fuel and its Applications," page 709) a direction which such methods might usefully take.

Illustration of the insufficiency of present methods is afforded by the results of the elaborate trials of fuel in quantity for steam raising which were carried out under the auspices of the Industrial Society of Mulhouse, whose "Bulletin" (already referred to) contains the records.

Even with calorimetric estimations of heating power, considerable variations from the calculated or theoretical figures have been obtained, as is shown by the following Table of examples of the results obtained by Messrs. Scheurer-Kestner and Meunier-Dollfus[1] and published by them and by Dr. Percy:[2]

TABLE XI.

	Description of Coal.	Locality.	Percentage composition of the Coal Exclusive of Ash and Water.			Calorific Power calculated on the dry Coal free from Ash.		Coke pr. cent. calculated on the dry Coal free from Ash.
			Carbon.	Hydrogen.	Oxygen and Nitrogen.	Experimental Calories.	Theoretical Calories.	
1	Lignite	Manosque, Basses Alpes	66·31	4·85	28·84	6991	5782	46·76
2	"	" " "	70·57	5·44	23·99	7363	6533	47·55
3	not stated	Louisenthal, Saarbrück	76·87	4·68	18·45	8215	7056	59·49
4	" "	Duttweiler, Saarbrück	83·82	4·60	11·58	8724	7871	63·58
5	" "	Ronchamp	88·38	4·42	7·20	9117	8354	71·58
6	Caking	Creusot	88·48	4·41	7·11	9622	8384	80·42
7	non-caking	"	90·79	4·24	4·97	9293	8585	84·12
8	Anthracite	"	92·36	3·66	3·98	9456	8553	88·15

These results exhibit differences of a striking character between the theoretical and experimental calorific power in all

[1] Annal. de Chim. et de Phys. s.4., 1870, xvi., p. 436; s.4 1872, xxvi., p. 80; see also M. L. Grüner's "Pouvoir Calorifique et Classification des Houilles," Ann. des Mines, 1874, p. 169.

[2] "Metallurgy," Vol. Fuel, p. 539.

cases, and also differences in value between specimens having practically the same ultimate composition on analysis. Of these latter Nos. 5 and 6 are examples, whilst 6 and 7 show other variations and anomalies in calculation from chemical composition. In all these cases which are noted in this Table, the experimental calorific power exceeded that obtained by calculation from the chemical composition, and the excess amounted in some cases to 15 per cent. In fact it may be taken as almost a general rule that higher heating effects may be obtained from fuel than a calculation of calorific power according to the usual methods would cause us to expect. It must not be assumed, however, that the thermal value yielded by experiment with a small quantity of coal burned in a calorimeter is necessarily the correct one, or is invariably the same even for the same coal. There are several sources of error in this method,[1] even with the best calorimeter in use, but it frequently yields higher results than calculation affords.

Theoretical Temperature of Combustion.—The employment of air in combustion necessarily exerts a considerable influence upon the temperature which is produced. If we had carbon burning in pure oxygen, the hypothetical maximum temperature which could be produced would be :—

$$T = \frac{P}{3{\cdot}6s}$$

$$i.e.\ T = \frac{8080}{3{\cdot}6 \times 0{\cdot}2164}$$

$$= 10{,}183^{\circ}\ \text{Cent.}$$

P being the calorific power of carbon = 8080.
3·6 being the quantity of carbonic acid produced per equivalent of carbon.
s being the specific heat of carbonic acid.

That is the result under the supposition that the carbonic acid as produced remains under constant pressure. Should the volume be kept constant instead of the pressure, Dr. Percy[2] has stated that the result will be greater in the ratio of 1 to 1·265, and hence that T will become

$$10{,}183 \times 1{\cdot}265 = 12{,}881^{\circ}\ \text{Cent.}$$

When air, supposed to consist exclusively of oxygen and nitrogen, is substituted for oxygen, and the quantity employed is that

[1] As to this, see "On the Calorific Value of Solid and Liquid Fuels," Jour. Soc. Chemical Industry, March 31, 1888 ; also ibid. 31 Oct., 1901, p. 972.
[2] "Metallurgy," vol. Fuel, p. 168.

which contains the exact proportion of oxygen required for the formation of carbonic acid, these temperatures become correspondingly

at constant pressure $= 2718^\circ$ Cent., and
at constant volume $= 3438^\circ$ Cent.

Similarly, the hypothetical maximum temperatures produced by the combustion of hydrogen appear to be [1]

in oxygen, under constant pressure	$= 6743^\circ$ Cent.
,, ,, ,, volume	$= 8779^\circ$ Cent.
in air, under constant pressure	$= 2684^\circ$ Cent.
,, ,, ,, volume	$= 3495^\circ$ Cent.

Effects of Air.—It will readily be understood that the temperatures obtainable in furnaces from the combustion of fuel must necessarily be considerably below these figures. Atmospheric air is a more complex mixture than in the case supposed above, being said to consist by volume of

$$0{\cdot}788N + 0{\cdot}197O + 0{\cdot}001CO_2 + 0{\cdot}014H_2O,$$
and by weight $0{\cdot}771N + 0{\cdot}218O + 0{\cdot}009CO_2 + 0{\cdot}017H_2O,$

so that the deductions to be made from the maximum hypothetical temperature are greater than those given. Then again, the practical conditions under which combustion of fuel takes place are such that it has always been found necessary, for complete combustion, to employ a greater or less excess of air over the quantity theoretically required to supply oxygen equivalent to the carbon and hydrogen in the fuel. This total quantity of air has to be heated to the temperature of the furnace, at the expense of the available heat from the fuel, and moreover, the large volume of gases resulting usually carries off a by no means inconsiderable proportion of this heat, part only being utilised in the so-called "ascensional power" of the gases, due to their expanded volume and correspondingly reduced weight.

The following Table, which was published in an interesting paper by Mr. W. H. Maw ("On Methods of Producing High Temperatures," Proc. Inst. Cleveland Engineers), some years ago, exhibits some of these facts in a convenient form. The number, 14,000, of heat units on the British scale has been

[1] See Percy's "Metallurgy," Vol. Fuel, pp. 167–173.

adopted for carbon, and the temperatures are given in Fahrenheit degrees :

TABLE XII.

Condition of combustion.	No. of units of heat produced.	Weight of products of combustion.	Mean specific heat of products of combustion.	Increase of temperature produced.
1 lb. of carbon burnt into carbonic dioxide. Oxygen supplied in a pure state.	14,000	lb. $3\frac{2}{3}$	0·216	$\frac{14,000}{3\frac{2}{3} \times 0·216} = 17,676°$ F
1 lb. of carbon converted into carbon monoxide. Oxygen supplied in a pure state.	4,000	$2\frac{1}{3}$	0·248	$\frac{4,000}{2\frac{1}{3} \times 0·248} = 6,912°$ F.
1 lb. of carbon burnt to CO_2. Oxygen supplied in atmospheric air.	14,000	13	0·237	$\frac{14,000}{13 \times 0·237} = 4,545°$ F.
1 lb. of carbon converted into CO. Oxygen supplied in air.	4,000	7	0·254	$\frac{4,000}{7 \times 0·254} = 2,249°$ F.
1 lb. of carbon burnt to CO_2. Oxygen supplied in air 20 per cent in excess.	14,000	$15\frac{2}{5}$	0·237	$\frac{14,000}{15·4 \times 0·237} = 3,836°$ F.
1 lb. of carbon burnt to CO_2. Oxygen supplied in air 50 per cent. in excess.	14,000	19	0·237	$\frac{14,000}{19 \times 0·237} = 3,109°$ F.

Loss of Heat from Opening Furnace Doors.—There is another cause of loss of heat, or failure to obtain the full result possible from a given fuel, the extent of which is very seldom estimated, and that is found in the frequent opening of furnace doors as required in the ordinary processes of stoking. In no furnaces are the evil effects of this so likely to be quickly experienced as in steam boiler furnaces, on account of the limited amount of fire brick surface and the large amount of metal surface exposed to the action of the flame and hot or cold gases. Each time the doors are opened there is an inrush of comparatively cold air from the stokehold, with consequent dilution of the hot gases and general reduction of the temperature ; and if Mr. Yarrow's estimate of 1,440 such openings in 24 hours (referred to in chap. II. *ante*) is at all near the mark, the loss of heat from this cause must be enormous.

Fluctuations of Temperature in Furnaces.—It has been recently said[1] that " when calculations are made for the transmission of

[1] " On the the Transmission of Heat through Plates from Hot Gases to Water," by Mr. George Halliday. Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xlii., p. 41.

heat through plates for a constant temperature of furnace and chimney, it must be understood that no such thing exists in practice, the temperature changing in the furnace 200° F. in less than a quarter of an hour, and the chimney varying within 100° in about the same time." It is probable, however, that Mr. Halliday's estimate is considerably below the mark. The

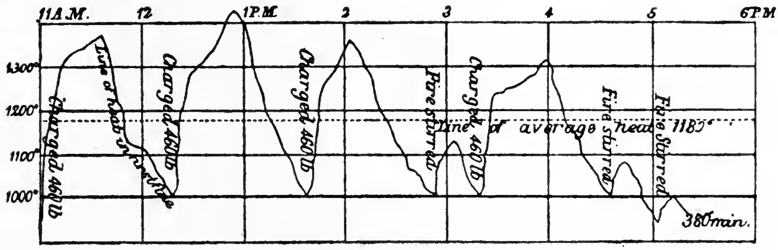


FIG. 33.

diagrams (see Figs. 33, 34, 35, and 36) of fluctuations of temperature in Mr. Houldsworth's trials, with carefully regulated hand stoking and chimney draught, show fluctuations of 400° F. due to opening firing doors and charging fuel every half hour; and where the fire was stirred between charges, the temperature did not again rise to its former point

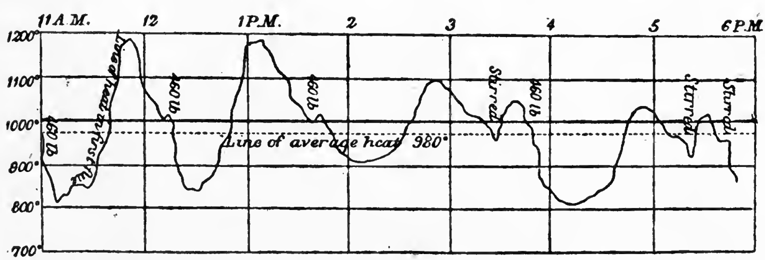


FIG. 34.

after each charge, so that it was on the average on a continual down grade. These diagrams were originally communicated to the Select Committee on Smoke Prevention in 1843, and are reproduced in Mr. D. K. Clark's "Steam Engine" (Vol. i., pp. 206–213). In Mr. Yarrow's estimate of the frequency of opening furnace doors, a large marine boiler, worked with forced

draught, is supposed, where consequently the combustion would be more rapid, and the necessity for charging and stirring fires more frequent.[1]

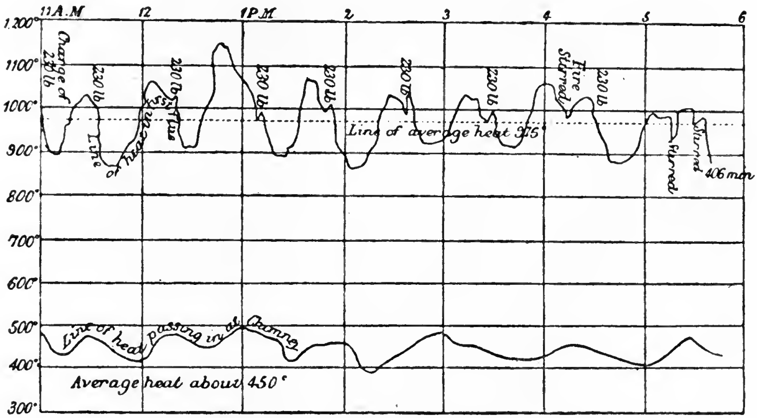


FIG. 35.

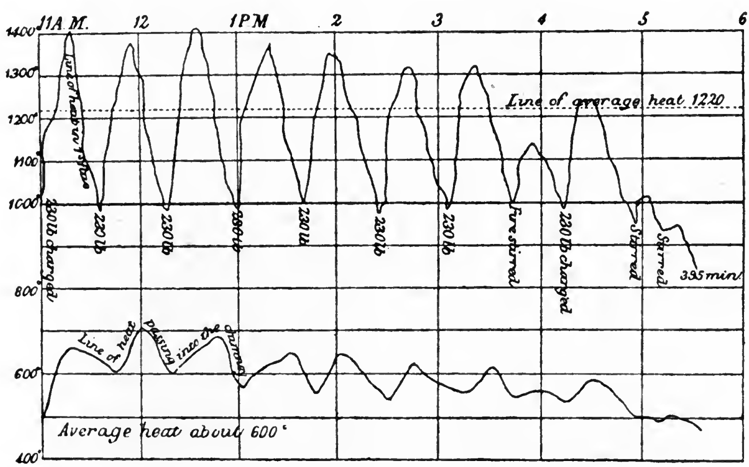


FIG. 36.

Various estimates of the actual temperatures produced in furnaces have been formed, and pyrometrical tests have been

[1] Refer also to D. K. Clark, "The Steam Engine," Vol. i., p. 295.

made by Mr. Isherwood, Mr. W. A. Martin, Mr. John Elder, Mr. D. K. Clark and others, but most of these suffer in their value from the exceedingly imperfect apparatus necessarily employed. With the pyrometers of Le Chatelier and of H. L. Callendar, there is now a much better opportunity than has ever previously occurred of obtaining continuous and accurate records of high temperatures.[1]

Quantity of Air Employed.—Whilst 12·2 lbs. of air supply the quantity of oxygen sufficient for the combustion of 1 lb. of carbon, it has been found that, with chimney draught, as much as from 18 to 22 lbs. of air per lb. of coal are necessary for the complete combustion of coal with ordinary grates and chimney draught, so that the presence of unconsumed carbon monoxide in the waste gases may be prevented. This is well illustrated in the tabulated results of trials given by Prof. Kennedy and Mr. Bryan Donkin in "Evaporative Trials of Steam Boilers." With the ordinary systems of forced draught in use there seems to have been little reduction made in that quantity, unless with water-tube boilers, which have shown 17·2 to 18·1 lbs. of air per lb. of coal with a fair economy in the consumption of fuel per I.H.P. hour.

Effects of Different Quantities of Air.—The following diagram was constructed by Mr. (afterwards Sir) William Anderson to exhibit graphically the effects produced on the temperature of combustion by the addition of different proportions of air to the fuel. Taking 12·2 lbs. of air and 5150° absolute (calculated thus—

$$T = 520^\circ + \frac{14{,}544 \text{ units.}}{13{\cdot}2 \text{ lbs.} \times 0{\cdot}238} = 5150^\circ \text{ absolute)}$$

as the theoretical temperature of combustion, with that quantity for a starting point, the curve for carbon shows the probable temperature with successive additions of air, making totals of 18·3, 24·4, and 36·6 lbs. of air per lb. of carbon. These quantities of air are set up as vertical ordinates to the base line in Fig. 37, the base line representing absolute zero and the horizontal lines above it various degrees of temperature on the

[1] See also "The Pneumatic Pyrometer, with Autographic Recorder," by E. A. Uehling. Cleveland Instn. of Engineers. January 22, 1900. Arndt's Apparatus. A. Bement. Jour. West. Soc. Engineers, Vol. vi., pp. 204–210.

absolute scale, those for the melting points of steel of different kinds having been carefully found. The upper curve illustrates similarly the combustion temperatures of petroleum composed of 0·84 of carbon and 0·16 of hydrogen, 1 lb. of the oil requiring only 10·32 lbs. of air theoretically for its complete combustion, and yielding with it 22,136 British heat units. The ordinates in

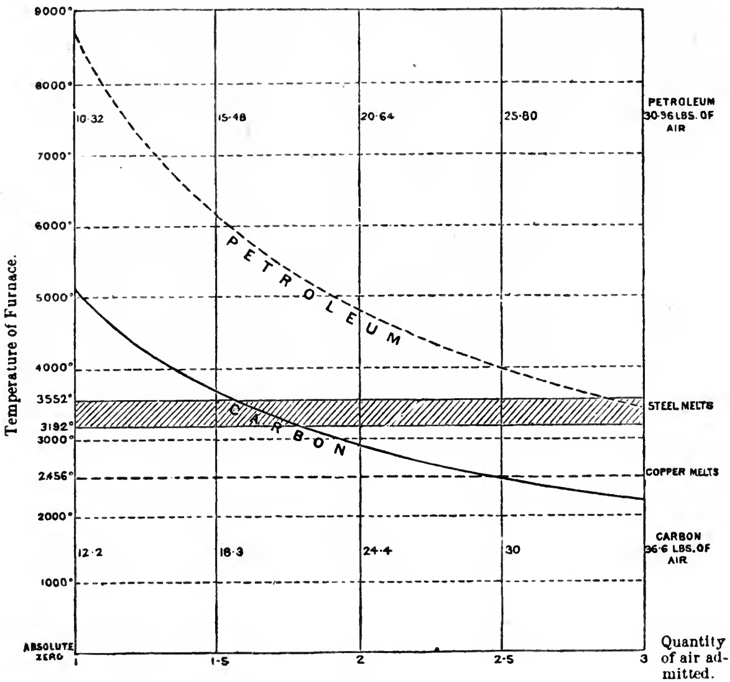


FIG. 37.

this case represent additions of air in quantities which are multiples of 10·32 lbs.

Volume of Gases from Combustion.—Professor Rankine calculated the volume of gases from the combustion in a furnace at temperatures from 32° to 4640° Faht. on the basis of 12 lbs. of air per lb. of fuel being supplied, and also at 18 lbs. and 24 lbs. of air per lb. of fuel. Ignoring variations of density produced by fluctuations of the pressure of gases in the furnace, above or below the mean atmospheric pressure, he assumed the volume

at 32° Fahr. to be $12\frac{1}{2}$ cubic feet for each lb. of air supplied to the furnace, so that with—

12 lbs. of air supplied per lb. of fuel, the volume of gases at 32° per lb. of fuel would be	150 cubic feet.
with 18	225 " "
" 24	300 " "

The volume at any other temperature T is calculated as follows :—

$$V = \text{volume at } 32^\circ \times \frac{T + 461^\circ{\cdot}2}{493^\circ{\cdot}2} = V_0 \cdot \frac{\tau}{\tau_0}$$

V_0 being = the volume at 32° of air supplied per lb, of fuel.
τ " = the temperature T on the absolute scale.[1]
τ_0 " = the absolute temperature of melting ice, *i.e.* 493°·2.

The results obtained by means of this calculation are given in Table XIII.

The velocity of the current of these gases in a chimney *in feet per second* is reckoned as follows:—

$$u = \frac{wV_0\tau_1}{A\tau_0}$$

w being = the weight of fuel burned in the furnace per second.
V_0 " = the volume at 32° of the air supplied per lb. of fuel.
τ_1 " = the absolute temperature of the gases discharged by the chimney.
A " = the sectional area of the chimney.

[1] *Absolute Temperatures.* (Rankine "Steam Engine," p. 228). The absolute zero is the imagined temperature corresponding to the disappearance of gaseous elasticity, at which $pv = 0$. Temperatures reckoned from that point are called absolute temperatures, and denoted by the symbol τ.
Let τ_0 be the absolute temperature of melting ice.
Let τ_1 be the absolute temperature of boiling water at atmospheric pressure.
Let τ be any third absolute temperature.
Then

$$\tau_0 = \frac{T_1 - T_0}{0{\cdot}365}$$
$$\tau_1 = 1{\cdot}365\,\tau_0$$
$$\tau = \tau_0 \frac{pv}{p_0v_0}$$

For Fahrenheit scale $\tau_0 = 493^\circ{\cdot}2$; $\tau_1 = 673^\circ{\cdot}2$; $\tau = 493^\circ{\cdot}2 \frac{pv}{p_0v_0} = T + 461^\circ{\cdot}2$.

For Centigrade scale $\tau_0 = 274^\circ$; $\tau_1 = 374^\circ$; $\tau = 274^\circ \frac{pv}{p_0v_0} = T + 274^\circ$.

The position of absolute zero on the Fahrenheit scale is—461°·2.
The position of absolute zero on the Centigrade scale is—274°.

TABLE XIII.

Temperature.	Volume of gases per lb. of fuel, in cubic feet, when air supply in lbs. of air per lb. of fuel is		
	12 lbs.	18 lbs.	24 lbs.
32° Fahr.	150 cub. ft.	225 cub. ft.	300 cub. ft.
68° "	161 "	241 "	322 "
104° "	172 "	258 "	344 "
212° "	205 "	307 "	409 "
392° "	259 "	389 "	519 "
572° "	314 "	471 "	628 "
752° "	369 "	553 "	738 "
1112° "	479 "	718 "	937 "
1472° "	588 "	882 "	1176 "
1832° "	697 "	1046 "	1395 "
2500° "	906 "	1359 "	1812 "
3275° "	1136 "	1704 "	
4640° "	1551 "		

The density of that current in lbs. to the cubic foot is, according to Rankine, very nearly

$$D = \frac{\tau_0}{\tau_1}\left(0{\cdot}0807 + \frac{1}{V_0}\right)$$

or from

$$0{\cdot}084 \text{ to } 0{\cdot}087 \times \tau_0 \div \tau_1$$

To calculate the "head," or height in feet, of a column of the hot gases in the chimney, which is required to produce the velocity u, Rankine uses the formula and constants given by Peclèt—

$$h = \frac{u^2}{2g}\left(1 + G + \frac{fl}{m}\right)$$

G being a factor of resistance to air passing through the fuel on a grate ascertained by Peclèt to be 12 for furnaces burning from 20 to 24 lbs. of coal per square foot of grate ;

f being a co-efficient of friction estimated at 0·012 by Peclèt ;

m being the hydraulic mean depth of chimney or one fourth of the diameter of a round chimney ;

l being the whole length of the chimney and flue in feet.

The formula then becomes—

$$h = \frac{u^2}{2g}\left(13 + \frac{0{\cdot}012l}{m}\right)$$

The head may be converted into an equivalent pressure in lbs. per square foot by multiplying it by the density as given above, *i.e.* $p = hD$, and this may be converted into any other unit of pressure by multiplying by a suitable factor.

For head in inches of water the multiplier is $\frac{1}{5{\cdot}204} = 0{\cdot}192$, so that head in inches of water $= 0{\cdot}192p$ or $0{\cdot}192\ hD$.

One lb. on the square inch $= 2{\cdot}307$ feet of water.

The following particulars of speed of gases with natural draught are taken from M. Bertin's work on "Marine Boilers."

"A column of air at 572° has a specific weight of about half that of the external atmosphere. If H be the height of the funnel above the grate bars, and the velocity be taken as uniform, the depression at the base of the funnel would $\frac{1}{2}$H.

"Expressing this in inches of water, we have :—

$$h = \tfrac{1}{2}H \times \frac{0{\cdot}0000466}{0{\cdot}03611} \times 12 = 0{\cdot}008\ H$$

when H equals the height of the funnel in feet, and h the height of the water column in inches. The weight of 1 cubic in. of air at 32° F. is 0·0000466 lb., and that of 1 cubic in. of water 0·03611 lb.

"Thus at the base of a funnel 66 ft., 49 ft., or 33 ft. high, the depression will amount to 0·53 in., 0·39 in., or 0·26 in. of water respectively, on the supposition that the mean temperature of the gases is 572° F., and that the movement of the column of air is not obstructed.

"It has been observed that the velocity of the air is 12·73 ft. on entering the ash pans for a depression of 0·52 in. in the ash pans, which corresponds to a depression of 0·43 in. in the furnace. If the air spaces between the furnace bars are equal to 60 per cent. of the grate surface, or say three times the section of the ashpit doors, the speed of the air though the bars will only be about 4·26 feet.

"Calculating the depression for a speed of 12·73 feet, we have :—

$$\Delta h = \frac{12{\cdot}73^2}{6900} = 0{\cdot}023 \text{ in.}$$

a very small fraction of the whole draught.

"At the base of the funnel the velocity of the gases is much greater than through the ashpans, on account of the reduced section, and also that the volume of the gases is increased, due to the increased temperature.

"To the weight of the column of air must be added also the weight of the products of combustion.

"Supposing the section of the funnel to be three-quarters of the section through the ashpits, the volume of the gas will be doubled when raised to 572°, and therefore the speed will be 2·66 times that through the ashpits. The increase of weight, amounting to about $\frac{1}{20}$, may be neglected. The value of $\Delta\ h$, therefore, at the base of the funnel may be taken to correspond to about :—

$$0{\cdot}023 \times 2{\cdot}66^2 = 0{\cdot}16.$$

"The energy absorbed in putting the column of gases in motion is small compared with that absorbed in overcoming the resistance of obstructions. Neglecting the resistance due to the ashpits, which is not great, the draught of 0·51 may be divided up as follows for a return tube boiler :—

Resistance due to funnel, uptakes, and smoke box	... ...	0·02 in.
„ „ tubes	... ...	0·11 „
„ „ firebox, bridge, furnace	... ...	0·06 „
„ „ fire of moderate thickness	... ...	0·31 „
„ „ inertia of column of gases	... ...	0·02 „
	Total ...	0·51

"In that division the total draught is measured from the fire-bars, neglecting the height of the smoke box where the draught is usually measured. The actual readings on the gauge would be 0·02 in. in the ashpit, 0·33 in. in the furnace, 0·39 in. in the combustion chamber at the back tube plate, and 0·51 in. in the smoke box. As a matter of fact the movement of the gases is by no means uniform and is subjected to great fluctuations. The following Table gives approximate velocities at various points, the grate area being taken as unity :—

TABLE XIV.

	Section.	Temperature Degrees F.	Approximate Velocity.
			Ft. per sec.
Ashpan doors	0·2	86	13·12
Air passages through grate	0·33		
Air passages through the coal	0·21 (assumed)	2912	91·86
Area above bridge	0·21	2192	75·46
Combustion chamber	0·21	1742	62·34
Entrance to tubes at back tube-plate ...	0·18	1292	49·21
Exit to tubes at front tube-plate	0·18	662	
Funnel...	0·15	572	32·81

"In tubulous boilers the section for the gases is generally very large when the gases leave the grate. Baffles are often employed to reduce the section and increase the length of the course of the gases through the tubes. Even with natural draught the gases sometimes reach the funnel too quickly. The bottom of the funnel which, under these conditions, is at a temperature of about 932° F., becomes a dull red and greatly increases the draught. This gives rise to the entry of an excess of cold air, and thereby reduces the efficiency of combustion. In a boiler where the gases have too short a course, too high a funnel may lead to bad combustion, but in general it is advisable to have a high funnel."

Effects of Pre-heating the Air for Combustion.—The economical effects of utilising the waste heat of the products of combustion for pre-heating the air which is introduced for burning the fuel have not been fully realised. There is no doubt that one of the

advantages derivable from the use of forced combustion or mechanically produced air-supply, is to be found in the facility which it offers for this preliminary heating of the air. The plan of a closed stokehold, however, used in vessels of the British Navy, does not lend itself to the process, as it would be manifestly impossible to raise the atmosphere of the stokehold in which men work to anything like a high temperature. Methods of suction draught are, however, quite as suitable as other plans for the addition of preliminary heating of the air supply for the furnaces, and these elements have been combined in one case at least. Wherever it is possible to introduce it, the increase of efficiency which may be realised from such pre-heating is undoubted.

In the case, for instance, of a pound of carbon burned to carbonic acid (referred to in Table XII. on page 59) with a supply of air amounting to 20 per cent. in excess of the theoretical quantity required for oxidation, and showing a theoretical resulting temperature of 3836° F., the effect produced by supplying the air for combustion heated (by means of the waste heat from chimney gases) to 400° above the normal atmospheric temperature, is considerable. It will amount to $14{\cdot}4 \times 400 \times 0{\cdot}238$, or about 1371 units of heat added to the furnace per lb. of carbon burnt.

The resulting temperature should in that case be—

$$\frac{14000 + 1371}{15{\cdot}4 \times 0{\cdot}237} = \frac{15371}{3{\cdot}6498} = 4211^\circ \text{ Faht.}$$

showing an increase of 375° F. in the temperature as compared with that produced without the preliminary heating of the air. In a paper "On Chimney Draught and Forced Combustion,"[1] by the author, another estimate was given. Supposing 1 lb. of average Newcastle coal to be capable of yielding 10,000 heat units and to be supplied with 24 lbs. of air for combustion which is heated, by transference of heat from the waste gases, to a temperature of 300° F. above the atmospheric temperature, then the result would be $300 \times {\cdot}2374$ (*i.e.*, the specific heat of air) $= 71$ units $\times 24$ (the air used for combustion) $= 1704$ units, or 17 per cent. would be added to the 10,000 units produced with air of normal temperature. Similarly if the temperature of the air

[1] Trans. Inst. Eng. and Shipbuilders in Scot. Vol. xxxii. (Dec., 1888.) See also "On Combustion." Jour. Soc. Chem. Ind. Vol. 1883, p. 79.

supply were increased by 600° and 1000° F., the augmentation of efficiency would be respectively $24\frac{1}{2}$ and 57 per cent. In other words, with an air supply exceeding the normal atmospheric temperature by 300°, 600° and 1000° F., 17 cwts., 15 cwts., and 9 cwts. of coal would respectively perform the duty of 1 ton if burnt with a similar weight of air at ordinary temperature. Plans for pre-heating the air used for combustion have been in use in ordinary furnaces and in gas furnaces on land since 1843, as may be seen by reference to the following works: Dr. Percy's "Metallurgy," Vols. "Fuel," p. 518; "Iron and Steel," p. 716; Tunner's "Eisen-hüttenwesen in Schweden": D. K. Clark's "Fuel, its Combustion, etc."; Mills and Rowan's "Fuel and its Applications." pp. 660-692, etc., whilst the value of heated blast in iron smelting furnaces has been elaborately worked out by Sir I. Lowthian Bell.[1] In Sennett and Oram's work on "The Marine Steam Engine" (1898) it is stated that "the development of the air-heating principle in this country is due principally to Mr. Howden of Glasgow," but it is evident that (as perhaps the authors meant) this statement applies only to the combination of such apparatus with forced draught in marine boilers with the ordinary grate or internal furnace.

Temperature of Exit Gases.—Another point which demands consideration is that of the temperature at which the waste gases are allowed to escape into the air, as this temperature determines the quantity of heat which is uselessly dissipated, and thus fixes the lower limit from which the useful effect of the fuel or boiler can be calculated.

Taking the average quality of Newcastle coal as above for an example, with 24 lbs. of air per lb. of coal for combustion, the waste gases would amount to 25 lbs., with the following result as to heat absorption: *i.e.*

Gases.	lbs.		Specific heat.		Heat units.
Carbon dioxide	3·7	×	·217	=	·8029
Oxygen	2·8	×	·218	=	·6104
Nitrogen	18·5	×	·244	=	4·5140
	25·0			=	5·9273

heat units required to raise these gases 1° Faht.

[1] See "Principles of the Manufacture of Iron and Steel," by I. Lowthian Bell, F.R.S. London, 1884.

Consequently if these gases were discharged into the chimney at 600° F. above the initial atmospheric temperature, $5 \cdot 9273 \times 600 = 3556$ heat units out of a possible 10,000, or $35\frac{1}{2}$ per cent. would be entirely lost or absorbed in draught production. If these gases were discharged at 1000° F. above the atmosphere, the loss with the same consumption of air would reach 5927 heat units, an amount considerably exceeding one half the entire calorific value of the fuel.[1]

With draught produced only by means of the ascent of hot gases in the chimney, the temperature which it is considered most advantageous (from the point of view of draught production) for these gases to have is 600° F. In certain cases, however, as for instance in that of the boilers of the s.s. "Propontis," and other examples of the same plans,[2] a chimney temperature of not more than 480° F. was obtained, along with the best results as to economy in consumption of fuel in these boilers, which was due to their having a very large proportion of heating surface per horse power and being wrought with slow combustion.

In some marine boilers, worked with forced or mechanically produced (sometimes called "accelerated") draught, either air-heaters or feed-water heaters (or "economisers") have been introduced in the uptakes or upper portions of the boiler casings, or in the space immediately above the boiler and between it and the chimney, in order to lower the temperature of the escaping gases as much as possible. Where feed-water heaters alone are used it is apparent, as Mr. Anderson remarked in his lecture[3] on "The Generation of Steam and Thermodynamic Problems Involved," that the chimney temperature cannot be lowered below the temperature of the feed water, and the limits of economy in such an application are soon reached.

There is no reason, however, why both kinds of heaters should not be simultaneously employed in order to utilise as much of the waste heat as is possible.

[1] Some interesting figures on the subject are given by Mr. Howden in his paper on "Forced Combustion in Steam Boilers." Proc. International Engineering Congress, Chicago, 1894. Vol. ii., Paper No. xlii., Page 12.

[2] See "On the Introduction of the Compound Engine and the use of High Pressure Steam," etc., by F. J. Rowan. Trans. Inst. Eng. and Shipbuilders in Scotland. Vol. xxiii., p. 15.

[3] Proc. Inst. C. E., 1883-84.

A further step in economy of heat would no doubt be realised by the addition of an auxiliary air condenser to the main engines, making the cold air, as drawn by the fans or blowers, to pass through or among tubes, having the exhaust steam from the low pressure cylinders in contact on the opposite surfaces of the tubes, and thus effecting the first step in the condensation of the steam used in the main engines. The condensation would have to be completed by a water condenser, but as all the heat removed from this steam in the usual way—by means of circulating water in condensers—is lost by being carried out of the steamship by the water, it is clear that if a portion of this heat could be returned by means of air to the furnace from which it was originally derived, a saving would be effected.

A proposal was made some years ago by Mr. J. P. Wilson[1] to utilise the waste steam from the auxiliary steam engines on board ship for the purpose of heating air for combustion, and experiments made with this plan were said to have given good results. There is no reason why it should not do so, or why the larger quantity of heat available in the steam from the main engines should not also be used. Mr. James Howden claims to have proposed an air condenser with this object in 1860.[2]

Forced or Accelerated Draught.—It is unnecessary in the present state of engineering science to urge at length the advantages of forced or mechanical as against chimney draught. In this respect there is a great contrast between the present time and twenty years ago, as may be seen by a perusal of some remarks in an article in *The Engineer* of 30th August, 1878, page 152, reviewing the author's paper, in which forced combustion was advocated. A statement of these advantages will now, however, help to point out the way to further improvement. With mechanically produced draught there is :—

1. A considerable economy in the power required to produce the movement of the air and gases.

2. A greater rapidity and therefore increased intensity of

[1] See *Engineering*, 15 April, 1887.

[2] See Proceedings of the International Engineering Congress, Chicago, 1894. Vol. ii., Paper No. xlii., page 14.

combustion is possible, by which means higher temperatures are produced in the furnace.

3. The velocity and direction of travel of the hot gases over the heating surfaces, as well as the escape of the waste gases, can be controlled without difficulty.

4. The incoming air for combustion can be made to pass through heaters exposed to waste heat, in various positions.

5. It is thus possible to lose or reject a smaller amount of heat in the gases or condensing water finally expelled.

Although it has become possible to burn large quantities of fuel per square foot of grate surface per hour, by means of the use of accelerated draught, and to do this with fairly good results, comparatively, as to economical evaporation per lb. of fuel burned, the full advantages of forced combustion have not yet been reaped.

Defects of Ordinary Systems of Forced Combustion.—The proportion of air introduced for combustion is still a long way in excess of the theoretical quantity, and the fluctuations of heat in the furnace are not prevented, but in many cases are increased in frequency. And finally the strain thrown upon the manual labour of stokers has been very greatly increased, and thereby the effect of the uncertain human factor, or "personal equation" of the stokers on the realisation of pre-determined results has been intensified. All the drawbacks experienced with the system are inherent to the use of the ordinary fire grates placed inside the boilers. These inside grates also render the application of mechanical methods of feeding the fuel extremely difficult of introduction, and the fluctuations in temperature are such that no very good result has been reached with any boiler, as yet, in the quantity of water evaporated per unit area of heating surface.

External Combustion Chambers.—The introduction of external combustion chambers will cause many of these difficulties to disappear; the coal can be continuously fed by mechanical means and the necessity for opening firing doors will be entirely abolished along with the necessity for human stokers. As nothing but a continual stream of flame and hot gases need be sent inside the boiler casing and throughout the heating surface, the evaporative efficiency of that surface may be maintained constantly at its highest point, always provided that the arrangements

for circulating the water in contact with that surface are adequate and efficient. Finally we have with this method the opportunity of applying combustion under increased pressure, the economic value of which has not been as yet acknowledged, nor have attempts been made to utilise it in any boiler introduced hitherto.

Economy in Power.—With regard to the economy of power represented by methods of forced draught, the following calculation from the French of M. Minary was given in "Fuel and its Applications" (pp. 385, 386). It is known that gases expand 0·367 of their volume for each 100° C. elevation of temperature. If we suppose the air which fills a chimney suddenly elevated 200° C. in temperature, its volume will become $1+(0{\cdot}367\times 2)=1{\cdot}734$. The internal capacity of the chimney being constant, all the increase of volume due to expansion escapes upwards.

The weight of a cubic metre of air, which at 0° C was 1·293 kilo., becomes at 200° C $\frac{1{\cdot}293}{1{\cdot}734}=0{\cdot}745$ kilo ; it has thus lost 0·548 kilo. per cubic metre.

Suppose a chimney of a square metre in sectional area, and of 20 metres height, the diminution of pressure at the base of the chimney will be for 200° C., 20 times 0·548, or 10·960 kilos., corresponding to a column of water 0·01096 of a metre, or nearly 11 millimetres high, which is the pressure at which the air will be supplied to the fire or furnace. Under the influence of this pressure, the expanded air will have a velocity of escape equal to 16·94 metres (equal to 55·56 feet) per second, after making deduction for friction and for resistance offered by the chimney walls and by changes of direction and of section.

This can be conveniently calculated in British standard measurements as follows: 1 cubic foot of air at 32° F. weighs ·0807 lb.; at 424° F. its weight becomes $\frac{{\cdot}0807}{1{\cdot}734}={\cdot}0046$ lb. The loss of weight is thus ·0761 per cubic foot.

Suppose a chimney of 1 square foot in sectional area, and 60 feet high, the diminution of pressure at the base will be for 424° F., $60\times{\cdot}0761=4{\cdot}566$ lbs. per square foot, or ·878 inch of water. Under this pressure, the ascensional velocity given by D K. Clark is as follows:—

$$v = 8\sqrt{H\left(\frac{T^1}{T} - 1\right)}$$ when H = height of chimney,
T^1 = highest temperature on absolute scale,
T = lowest temperature on absolute scale.

In the above case the calculation is :—

$$v = 8\sqrt{60\left(\frac{885}{493} - 1\right)} = 8\sqrt{60(1\cdot8 - 1)} = 8\sqrt{48} = 56 \text{ ft. per second nearly.}$$

Taking for example 1 kilo. of Blanzy coal, having the composition carbon 76·5, disposable hydrogen 3·1 per cent., the combustion of that quantity of this coal requires :—

Oxygen	2·288 kilos	=1·597 cubic metres
Nitrogen ...	7·660 „	=6·098 „ „
Air	9·948 „	=7·695 „ „

Calling that quantity of air 7·700 cubic metres, the resulting products of combustion, in escaping at 200° C., carry off 890 calories, or nearly $\frac{1}{8}$ part of the heat produced by the combustion of the coal.

The mechanical work necessary to supply a fire with 7·700 cubic metres of air at a pressure of a water column of 11 millimetres high, which corresponds to 10·100 kilos. per square metre, will be 10·100 × 7·700 = 77·7, or, in round numbers, 78 kilogrammetres. The mechanical equivalent of 1 calorie being nearly 425 kilogrammetres, we thus find that the heat dispersed into the atmosphere by the gases at 200° C. causes the disappearance of power equivalent to 890 calories × 425 = 378,250 kilogrammetres, in order to produce a useful effect equal to 78 kilogrammetres. The relation of the loss to the useful effect is thus, theoretically :—

$$\frac{378{,}250}{78} = \frac{4{,}849}{1}$$

To ascertain the practical relation of loss to useful effect, we have to allow for the useful effect of steam engine and fan. Engines give out only 0·055 per cent. of the power which is represented by the heat possessed by the steam, and the useful effect of fans is not more than 0·10 to 0·20. The practical relation which we wish to establish will therefore be expressed by:—

$$\frac{4\cdot849 \times 0\cdot0055}{1} = \frac{26\cdot66}{1}$$

which amounts to saying that to produce the movement of air in fires by the natural draught of chimneys, we spend 26 times as much heat as we should need to spend in order to produce the same effect by means of steam engines and fans.

In this calculation only the theoretical quantity of air required for combustion has been assumed, and it is certain that if a larger quantity were taken, the loss of heat by chimney draught would be much greater. Taking the example of the Newcastle coal, referred to on page 68, supplied with 24 lbs. air per lb. of coal, the loss of heat with waste gases at 392° F. (*i.e.*, $424^\circ - 32^\circ$) would equal 2,323 units per lb. of coal. This, expressed in units of power, means that $2{,}323 \times 772 = 1{,}793{,}356$ foot-lbs. are expended in draught production. The actual mechanical energy which would be required to supply 300 cubic feet of air at a pressure of ·878 inch of water, or 4·566 lbs per square foot, amounts only to $300 \times 4{\cdot}566 = 1{,}370$ foot-lbs., plus the amount required to overcome friction, and to make up for loss of efficiency in engine and fan.

Mr. James Howden (in Trans. Inst. N.A., 1884) compared the expenditure of power as heat required for natural draught in a steamer, the boilers of which consume 31,200 lbs. of coal per hour, 520 lbs. per minute (*i.e.*, 12,000 I.H.P. at 2·6 lbs. coal per hour per I.H.P.), with the power required for mechanical supply of air for boilers to provide the same power, but consuming only 1·6 lbs. per I.H.P. per hour = 19,200 lbs. per hour (320 lbs. per minute). He also supposed the air supply to be 15 lbs. per lb. of coal consumed in both cases, but *assumed* that the waste gases with mechanical supply would have a temperature 300° F. less than those with natural draught. In the first case, $520 \times 15 = 7{,}800$ lbs. weight of air supplied per minute for combustion, the weight of gaseous products of combustion being reckoned at 8,281 lbs. This $8{,}281 \times {\cdot}246$ (specific heat of the waste gases) $\times 300^\circ$ (excess of temperature as above) $= 611{,}137$ heat units, the expenditure of heat in this case. The mechanical equivalent of this is $\frac{611{,}137 \times 772}{33{,}000} = 14{,}296$ H.P. "This, of course, supposes the total heat converted into work and expressed in H.P. units. The actual value of this expenditure of heat is correctly stated in the ratio of the economy of the engines and boilers which, at 2·6 per I.H.P. per hour is very

nearly a utilisation of one-twelfth of the total heat of combustion of coal of average quality; therefore $14,296 \div 12 = 1,191$ is the actual H.P. equivalent of the 300° of heat lost in maintaining the temperature of the funnel in the natural draught boilers."

In the other case, $320 \times 15 = 4,800$ lbs. of air per minute would be required for combustion. "The volume required at 60°, or 13 cubic feet per lb., is therefore $4,800 \times 13 = 62,400$ cubic feet.

"To supply this volume per minute from three fans, each having discharge orifices 30 inches diameter, or 6·25 square feet area, giving a total area of 18·75 square feet, a velocity of 55·46 feet per second is required, as $18{\cdot}75 \times 60 \times 55{\cdot}46 = 62,400$. The H.P. required to supply this weight of air at this velocity per second is found by the usual formula, $\frac{Wv^2}{2g}$. Here $W = \frac{4800}{60}$ or 80 lbs. air per second, and $\frac{80 \times 55{\cdot}46^2}{64} = 3,845$ foot-lbs. per second, and $\frac{3,845}{550} = 7$ H.P. nearly. This 7 H.P. is the power required to supply the whole air of combustion for 12,000 I.H.P., supposing perfect efficiency in the fans and in the engines that drive them. Assuming 75 per cent. efficiency in the engines, and 50 per cent. in the fans, we have $\frac{7 \times 100}{75} = 9{\cdot}3$, and $\frac{9{\cdot}3 \times 100}{50} = 18{\cdot}6$ as the gross H.P. for supplying the total air of combustion to the furnaces mechanically."

The relative economy in this supposed case is as 18·6 is to 1,191, but of course it would not be in the same proportion if a smaller consumption of coal in the natural draught boilers, or a less difference in the final temperature of the waste gases, were assumed.

Rapidity and Intensity of Combustion.—The increased rapidity and intensity of combustion are well illustrated now in the numerous accounts of trials of boilers under "natural draught" and under "forced draught" which have been published.

Admiralty System.—The late Mr. Richard Sennett, Engineer-in-Chief of the Navy, gave the following results of the Admiralty plan with closed stokeholds, shown in Figs. 38, 39, 40, in a paper in "Transactions of the Institute of Naval Architects in 1886."

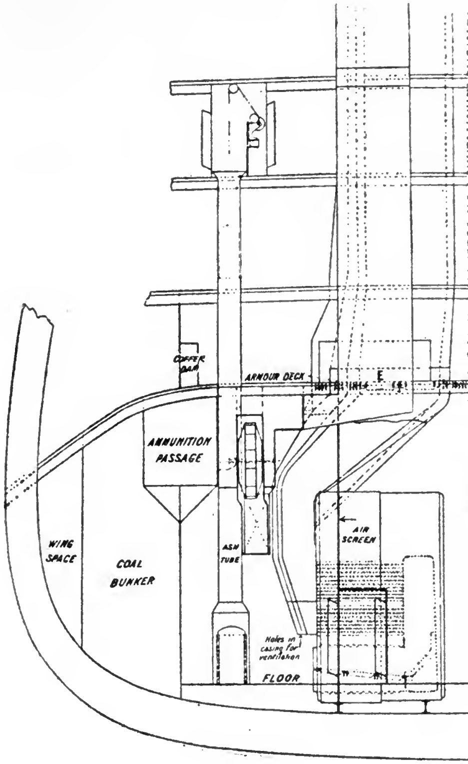


FIG. 38.

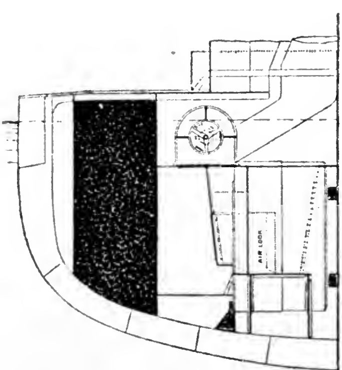


FIG. 39.

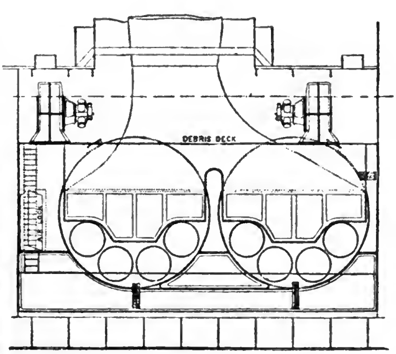


FIG. 40.

TABLE XV.

1.	2.	3.	4.	5.	6.	7.	8.
						Indicated Horse-Power per	
Ship.	Date.	Load on Safety Valves.	Indicated Horse Power.	Weight of Boilers.	Area of Firegrate.	Square Foot of Firegrate.	Ton of Boiler.
Open Stokeholds.		lb.		tons.			
"Inflexible"	1878	60	8,484	756	829	10·21	11·22
"Colossus"	1883	64	7,492	594	645	11·62	12·61
"Phaeton"	1884	90	5,588	462	546	10·23	12·1
Forced Draught.							
"Howe"	1885	90	11,725	632	756	15·54	18·5
"Rodney" (9 boilers) ...	1885	90	9,544	474	567	16·83	20·1
"Mersey"	1885	110	6,628	306	399	16·61	21·7
"Scout"	1885	120	3,370	174	207	16·28	19·3
"Trafalgar" (estimated) ...	...	135	12,000	514	609	20·00	23·3

NOTE.—The weight of boiler given includes weight of water, funnel, uptakes fittings, spare gear, etc.

Mr. Sennett remarked on these figures :—

By referring to the seventh column of this Table, it will be seen that whilst in the ships with natural draught only, about 10¼ indicated horse-power was developed per square foot of firegrate, between 16 and 17 indicated horse-power was obtained with moderate forced draught, the boilers being practically the same in the two cases. The steam blast ws used throughout the trial of the "Colossus."

The grate area can only be used as a fair basis of comparison for boilers similar in design and construction. I have, therefore, in the last column, given the indicated horse-power developed per ton weight of boiler, which s the more important feature, so far as the naval architect is concerned, and we see from this column that the effect of the application of forced draught has, been to increase the power obtained from a given weight of boilers in the proportion roughly of 20 to 12, the engines and boilers being of practically the same description in both cases.

In the "Nile" and "Trafalgar," and other warships now building, triple expansion engines will be fitted, worked with steam of 130 lb. to 140 lb. pressure per square inch. From the experience we have now gained respecting the steam generating powers of boilers in closed stokeholds kept under moderate air pressure, and the well-known economical employment of steam in triple-expansion engines, we are satisfied that on the full power trials of these vessels at least 20 I.H.P. per square foot of grate, and between 23 and 24 I.H.P. per ton of boiler will be realised, and this condition has been readily accepted by the engine contractors who have had experience of the working of the system.

The two following Tables were also given by Mr. Sennett, and furnish full details of the machinery and of the trials of the various ships. From the abstract of steam trials, the rate of combustion per square foot of grate area can be calculated in all but the second trial of the "Rodney," and the figures have been added to the Table as published by Mr. Sennett. The insertion of three examples of vessels worked with open stokeholds and only partial use of blast enables a comparison to be made.

TABLE XVI.—PARTICULARS OF MACHINERY.

Particulars.	"Inflexible."			"Colossus."		"Phaeton."	"Mersey."	"Scout."	"Rodney" and "Howe."	"Trafalgar" proposed.
Description of engines		3 cylindrical vertical compound.		3 cylindrical vertical compound		Horizontal compound	Horizontal compound	Horizontal compound	3 cylinder vertical compound	Vertical triple expansion.
Diameters of cylinders in inches — High pressure		2 of 70 in.		2 of 58 in.		2 of 42 in.	2 of 38 in.	2 of 26 in.	2 of 52 in.	2 of 43 in. 2 intermediate of 62 in.
Diameters of cylinders in inches — Low pressure		4 of 90 in.		4 of 74 in.		2 of 78 in.	2 of 64 in.	2 of 46 in.	4 of 74 in.	2 of 96 in.
Length of stroke...		4 ft.		3 ft. 3 in.		4 ft.	3 ft. 3 in.	2 ft. 6 in.	3 ft. 9 in.	
Propeller — Description... ...		2 bladed		4 bladed		4 bladed	3 bladed	3 bladed	4 bladed	Not yet decided.
Propeller — Diameter		20 ft. 2¼ in.		17 ft. 8½ in.		14 ft. 0½ in.	13 ft.	10 ft. 6 in.	15 ft. 6 in.	
Propeller — Pitch...		23 ft. 0½ in.		18 ft. 7¼ in.		20 ft. 1¾ in.	18 ft. 5⅞ in.	12 ft. 6 in.	19 ft. 6 in.	
Boilers — Number		12		10		8	6	4	12	6
Boilers — Description ...	Oval 3 furnace	Four each of Oval 2 furnace.	Oval double ended 4 furnace	Eight Oval 3 furnace	Two Oval 2 furnace	Cylindrical high 3 furnace	Low cylindrical 3 furnace	Low cylindrical 3 furnace	Oval 3 furnace	High cylindrical 4 furnace
Boilers — Transverse dimensions	13 ft. 7 in. × 15 ft. 6 in.	11 ft. 1 in. × 13 ft. 4 in.	9 ft. 4 in. × 14 ft. 3 in.	12 ft. 9 in. × 15 ft. 3 in.	7 ft. 10 in. × 14 ft.	13 ft. 5 in. dia.	10 ft. dia.	9 ft. 3 in. dia.	11 ft. × 15 ft.	16 ft. 2 in. dia.
Boilers — Length	9 ft.	9 ft.	17 ft.	9 ft. 9 in.	9 ft. 9 in.	9 ft. 8 in.	18 ft. 9 in.	17 ft. 10 in.	9 ft. 8 in.	10 ft. 3 in.
Load on safety valves		60 lb.		64 lb.		90 lb.	110 lb.	120 lb.	90 lb.	135 lb.
Furnaces — Number		36		28		24	18	12	36	24
Furnaces — Diameter	Twelve of 3 ft. 6 in.	Eight of 3 ft. 3 in.	Sixteen of 3 ft 6 in.	Twenty-four of 3 ft. 5 in.	Four of 2 ft. 10 in.	18 of 3 ft. 3 in. 6 of 3 ft.	3 ft. 2 in.	2 ft. 10 in.	3 ft.	3 ft. 7½ in.
Furnaces — Length	6 ft.	6 ft.	6 ft. 6 in.	6 ft. 9 in.	6 ft. 9 in.	7 ft.	7 ft.	6 ft.	7 ft.	7 ft. 4 in.
Furnaces — Grate area in sq. ft.		829		645		546	399	207	756	609
Heating surface of boilers in sq. ft. — Tubes ...		18,654		14,747		12,456	10,367	5500	17,174	17,040
Heating surface of boilers in sq. ft. — Total ...		22,288		17,507		14,562	11,700	6170	20,294	19,390
Area through tubes in sq. ft. ...		158		117		87·5	61	32	102	96
Funnels — Number		2		1		2	1	1	2	2
Funnels — Size		Oval 10 ft. × 8 ft.		Oval 12 ft. × 8 ft.		8 ft. dia.	7 ft. 2 in. dia.	6 ft. 6 in. × 4 ft. 9 in.	9 ft. × 5 ft. 6 in.	7 ft. diameter
Funnels — Height above firebars		70 ft. 3 in.		...		61 ft. 8 in.	52 ft. 6 in.	55 ft.	75 ft.	65 ft.
Ratios of — Tube heating surface / Grate area		22·5		22·8		23·3	25·9	26·5	22·7	28
Ratios of — Area through tubes / Grate area		·190		·181		·160	·152	·154	·134	·158
Ratios of — Area of funnels / Grate area		·160		·128		·183	.100	·125	·114	·126
Forced draught fans — Number ...		...		...		...	4	4	8	6
Forced draught fans — Diameter ...		...		...		...	5 ft.	3 ft. 6 in.	5 ft.	5 ft. 6 in.

TABLE XVII.—ABSTRACT OF STEAM TRIALS.

	Open Stokeholds.			Forced Draught.					
	"Inflexible."	"Colossus."	"Phaeton."	"Mersey."	"Scout."	"Rodney."		"Howe."	"Caroline."
Date of trial	Nov. 14, 1878.	Jan. 10, 1884.	Feb. 12, 1884.	Sept. 24, 1885.	Sept. 23, 1885.	June 13, 1885.	June 16, 1885.	Jan. 14, 1886.	Mar. 4, 1885.
Duration of trial in hours	6	5	5	3	4	4	3	4	6
Number of boilers used	12	10	8	6	4	12	9	12	2
Mean steam pressure in boilers ... lb.	61.06	61.52	85.35	107.8	113.09	93.06	92.74	89.21	84.52
" air pressure in boiler rooms, inches of water	...	...	...	2.02	1.52	1.4	1.89	2.05	1.5
Mean pressure in cylinders in pounds per sq. inch { High-pressure	29.55	40.66	43.56	56.53	61.42	59.92	49.73	59.51	43.9
{ Low "	9.833	2.09	11.43	22.82	24.31	12.8	12.1	13.43	12.79
Mean revolutions per minute	73.26	89.96	100.26	122.34	152.33	103.42	100.13	106.63	77.8
" speed of piston, in feet, per minute	586	585	802	795	762	776	751	800	389
Indicated horse-power	8483	7492	5588	6628	3370	11,158	9544	11,725	983
Area of firegrate used in square feet ...	829	645	546	399	207	756	567	756	54.5
I.H.P. per square foot of firegrate	10.21	11.62	10.23	16.61	16.28	14.75	16.83	15.51	18.02
Heating surface per I.P.H. in square feet { Tubes ...	2.20	1.97	2.23	1.56	1.63	1.54	1.35	1.46	1.24
{ Total ...	2.63	2.33	2.61	1.77	1.83	1.82	1.6	1.73	1.43
Coal used per I.H.P. per hour, in pounds ...	2.06	2.55	2.39	2.48	2.6	2.2	...	2.16	2.54
" hour, in tons	7.80	8.53	5.96	7.33	3.92	11	...	11.30	1.11
Remarks	Blast used last half hour only.	Blast used throughout the trial.	Natural draught only.						
Combustion per square ft. of grate area in lbs....	21.02	28.93	24.44	41.25	42.32	32.45	...	33.5	45.77

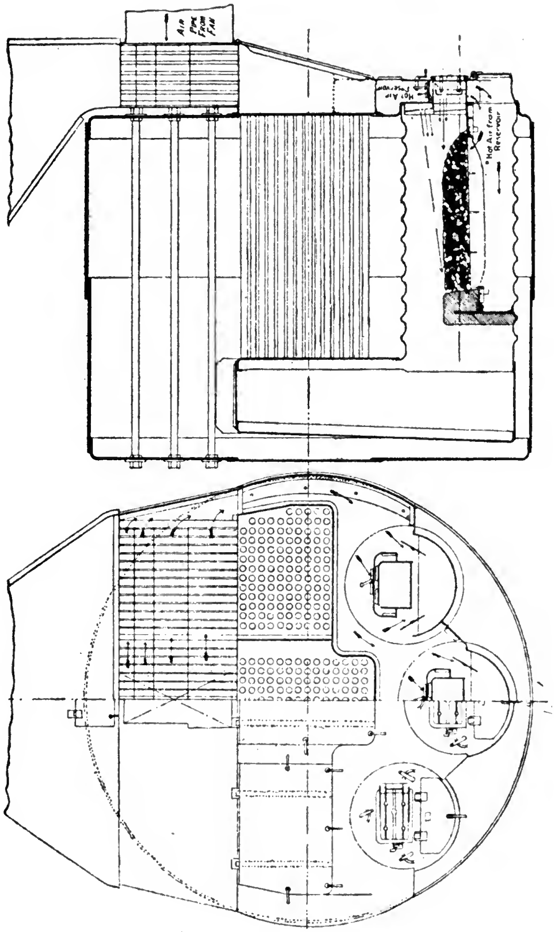
NOTE.—The indicated horse-power recorded is that developed by the main engines only, and does not include the indicated horse-power expended in working the feed and circulating pumps, blowing fans, and other auxiliary machinery.

Howden's System.—In Mr. Howden's plan, which is illustrated in Figs. 41 and 42, as carried out in the s.s. "New York City," in 1884, the rate of combustion gave 17·4 I.H.P. per square foot of grate area on a consumption of coal equal to 1·337 lbs. per I.H.P. hour in one voyage, and in another voyage 19·6 I.H.P. per square foot of grate on a consumption of 1·454 lbs. per I.H.P. hour with inferior coal. About 6 I.H.P. were required for the fan engine. On a special occasion the full power was obtained (with steam blowing off at the safety valve) by the use of only two furnaces, which result Mr. Howden[1] reckons is equal to 30 I.H.P. per square foot of grate.

Air Heater.—The air for combustion was heated directly by the waste gases, in the heater placed in the uptake, to an average of 190° over the temperature of the air supply from the stokehold. Mr. Howden assumed $18\frac{1}{2}$ lbs. of air as the quantity used per lb. of coal, and in that event there were $190 \times 18{\cdot}5 \times {\cdot}238 = 836{\cdot}57$ units of heat recovered from the waste gases per lb. of coal consumed. It is supposed that the air is further heated by its passage over a portion of the boiler front and through the furnace boxes or passages, on Mr. Howden's plan, and there is no doubt that a small addition to the temperature may thus be gained. It could, however, scarcely reach 450° as Mr. Howden supposes it does, in the case of a boiler carrying steam of 80 lbs. pressure, because the temperature of the steam, and therefore of the boiler surfaces not exposed to the fire gases, could not in such a case be above 312° F. In the s.s. "Indiana," and sister ships, having boilers with 2,338 square feet of heating surface (or equal to 1·63 square foot per I.H.P.), and a total grate area of 56·5 square feet, of which, however, only 50 square feet constituted the working area, the rate of working (as published by Mr. Howden[2]) was $22\frac{1}{2}$ I.H.P. per square foot of total grate area, the temperature of the waste gases, when leaving the air-heating tubes, was from 420° to 450° F., and the temperature of the heated air was from 190° to 230° F. Mr. Howden estimates that the temperature of the

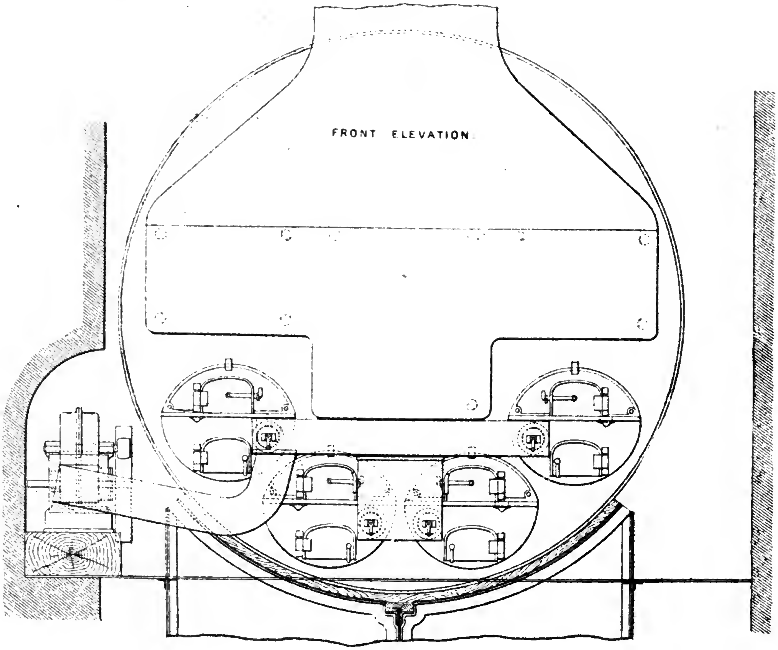
[1] See "Trans. Inst. N. A.," Vols. for 1884 and 1886, on "Combustion of Fuel in Furnaces of Steam Boilers," and "On Forced Combustion in Furnaces of Steam Boilers," by James Howden.

[2] "Forced Combustion in Steam Boilers," "Trans. Internat. Engineering Congress, Chicago," 1894, vol. ii., paper xlii.



FIGS. 41 & 42.

air can be further raised, by increased heating surface, to 300° or 350° F., and that the average temperature of the furnaces when working as above would be 400° higher than it would be in the same boiler, burning the same quantity of coal, if fitted with the closed stokehold system of forced combustion with cold air. The air in the "Indiana" was supplied by a "Sturtevant" fan of 54 inches diameter.



Scale ½ Inch = 1 Foot

FIG. 43.

Closed Ashpit System.—The closed ashpit system, illustrated in Figs. 43 and 44, has been introduced in several forms. Mr. G. Ferrando's plan was used in several steamers belonging to Messrs. Florio Rubbatino and Co., of Genoa, and was found satisfactory for moderate rates of combustion at about 20 lbs. of fuel per square foot of grate surface. With higher rates of combustion there was a danger of the flame being forced through the furnace doors, on account of the funnel being

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unable to discharge the large volume of waste gases. An improved method of distributing the air was introduced in the s.s. "Marmora," by Mr. Fothergill, with good results.[1] A recent example of the closed ashpit system was fitted by Mr. D. J. Dunlop[2] in the steam yacht "Mira," in which 1 H.P. was obtained from 1·45 square feet of heating surface of the boilers,

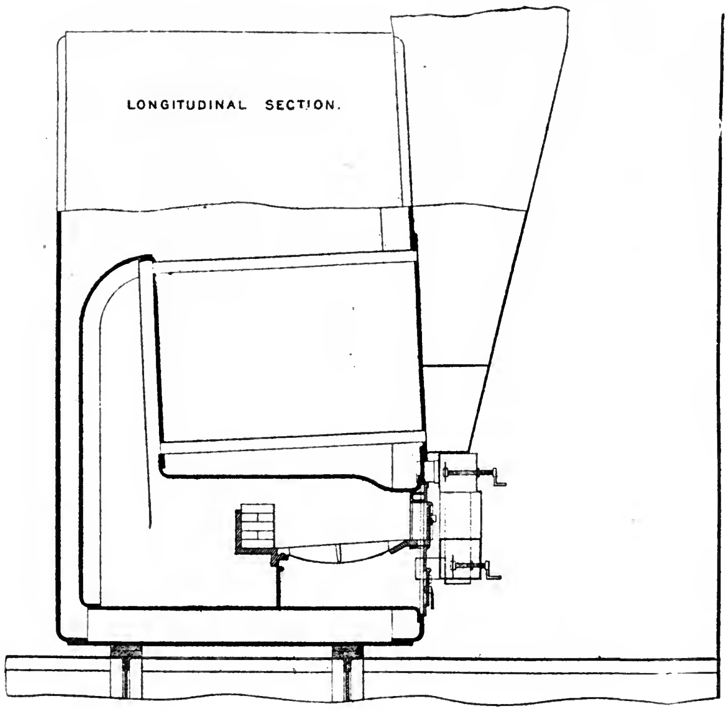


FIG. 44.

and 21·66 H.P. per square foot of grate surface. The total heating surface was 1,317 square feet, and the grate area 42 square feet. The steam pressure was 160 lbs. per square inch, and the total I.H.P. 907, the weight of machinery being at the rate of 207 lbs. per I.H.P.

[1] See "Trans. N.E. Coast of Engineers and Shipbuilders, 1886," Vol. ii.
[2] *Engineering*, 18th March, 1892, p. 351.

Suction System.—Ellis & Eaves' Plan.—The use of a fan for exhausting the products of combustion, or producing a partial vacuum at the base of the funnel, has been introduced in the plans of Ellis & Eaves and of Patterson. This system has been called "Induced," but more commonly "Suction" or "Exhaust" draught.

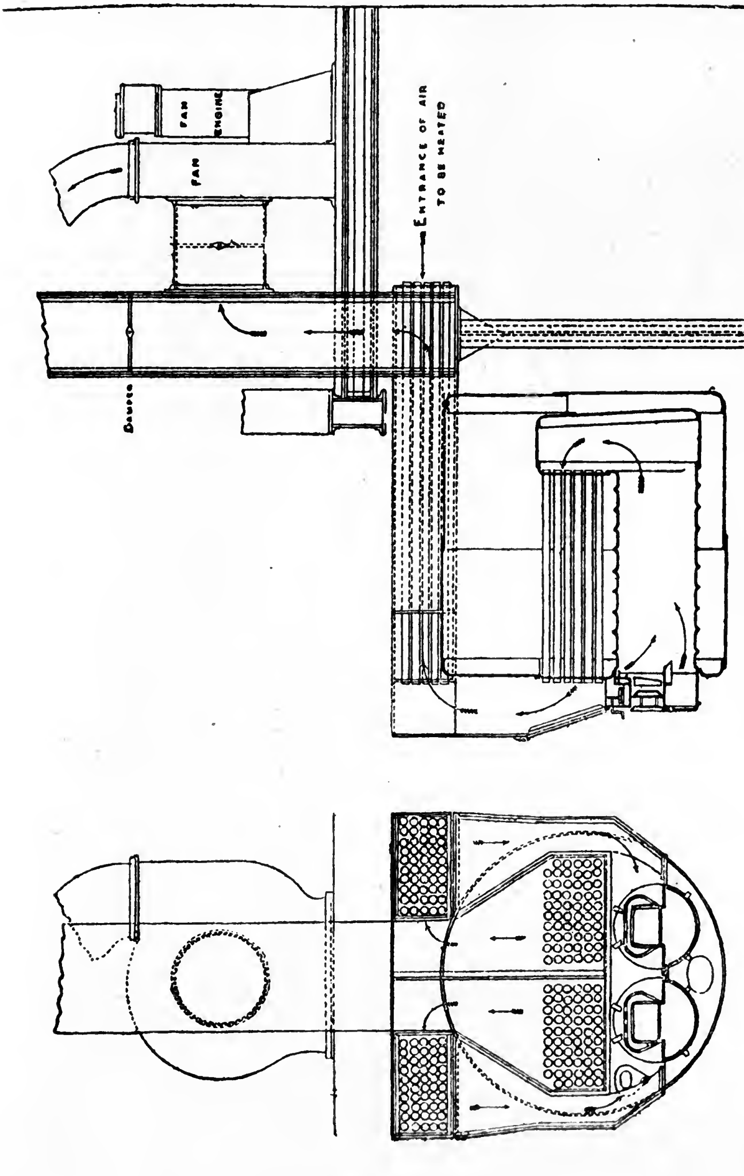
In the case of the former of these plans illustrated in Figs. 45 and 46, with a grate of 5ft. 9in. long, a rate of combustion of 30 to 60 lbs. per square foot of grate surface has been obtained in marine boilers of the "Scotch" or cylindrical kind on land, and of 26 to 31½ lbs. per square foot at sea in the Atlantic and Australian merchant services, "without troubles to furnaces, tube plates, tube ends, fans and fan engines, accompanied by an appreciable economy compared with the boilers of the same size, with plain tubes working with natural draught at half the rate of combustion." In the Ellis & Eaves' plan the use of an exhaust fan is combined with that of the "Serve" or internally ribbed tube, generally with a specially shaped retarder for the gases added inside the ribs, and with air-heating tubes in the waste gases carried to a greater extent than in other plans.

Table XVIII.[1] gives the principal dimensions and results of working in the case of five steamers fitted with this plan.

Mr. Howden has advanced[2] some considerations to prove that a considerable increase of power is required to drive fans on this system, as compared with his own plan of delivering the air for combustion at a slight pressure into the furnace and ash-pit, but it is not our province to enter into this argument. There is probably more power required on account of the larger volume of products to be dealt with in given time, and probably also because a greater amount of vacuum is required at the smoke-box end, on the suction plan, than of pressure at the furnace end of the system, on the forcing plan. On the other hand it may be the case that with the suction plan a greater velocity of movement of hot gases over the heating surfaces is obtained, and this, if carefully utilised, may cause a better result

[1] See Paper by J. D. Ellis. Trans. Inst. N. A. 1893. Also Paper by F. Gross. Trans. Inst. N. A. 1894.

[2] Proceedings of the International Engineering Congress at Chicago. 1893. Vol ii., paper xlii.



FIGS. 45 & 46.

TABLE XVIII.—PARTICULARS OF SHIPS AT WORK WITH THE "ELLIS AND EAVES" COMBINATION DRAUGHT.

	S.S. "Berlin."	S.S. "Southwark."	S.S. "Kensington."	S.S. "Perthshire."	S.S. "Buteshire."
Length of ship	488 ft. 6 in.	480 ft.	480 ft.	435 ft.	435 ft.
Width of ship	44 ft. 0 in	57 ft.	57 ft.	54 ft.	54 ft.
Depth of ship	36 ft. 9 in	40 ft.	40 ft.	32 ft.	32 ft.
Displacement at trial trip	—	12,300 tons.	12,400 tons.	7,500 tons.	—
Number of boilers	8 single ended.	2 double ended & 1 single ended.	2 double ended & 1 single ended.	2 single ended.	2 single ended.
Size of boilers	13 ft. 2½ in. mean dia. × 11 ft. 4½ in.	15 ft. $9\frac{3}{16}$ in. m. dia. × 21 ft. 8¾ in. 15 ft. $9\frac{3}{16}$ in. m. dia. × 11 ft. 1 in.	15 ft. 9 in. m. dia. × 21 ft. 7 in. 15 ft. 9 in. m. dia. × 11 ft. 5 in.	15 ft. 6 in. mean dia. × 12 ft.	15 ft. 6 in. mean dia. × 12 ft.
Number of furnaces	24	20 Purves.	20 Purves.	6 Purves.	6 Purves.
Inside diameter of furnaces	3 ft. 2 in.	3 ft. 4 in.	3 ft. 4 in.	3 ft. 9 in.	3 ft. 9 in.
Length of grate	5 ft. 3 in.	5 ft. 9 in.	5 ft. 9 in.	5 ft. 9 in.	5 ft. 9 in.
Total heat-distributing surface in boilers reckoning outside surface of tubes	14,616 sq. ft.	12,285 sq. ft.	11,672 sq. ft.	4,770 sq. ft.	4,770 sq. ft.
Total grate surface	396 sq. ft.	383 sq. ft.	383 sq. ft.	127 sq. ft.	127 sq. ft.
Working pressure	150 lbs.	200 lbs.	200 lbs.	160 lbs.	160 lbs.
Number of fans	4	5	5	2	2
Size of fans	7 ft. 6 in. dia.	7 ft. 6 in. dia.	7 ft. 6 in. dia.	8 ft. dia.	8 ft. dia.
Mean speed developed at trial trip	—	16·3 knots.	15·8 knots.	11·75 knots.	—
Average revolutions of fan engines	360	317	—	320	—
Number of voyages	17	4	—	1	—
Average I.H.P. of voyages	5,566	4,446	—	2,450 outwards.	—
Average coal consumption per I.H.P.	—	—	—	1·34 lbs. Newcastle Small.	—
Average coal consumption per square feet of grate...	26 lbs.	27·5 lbs.	—	31·5 lbs.	27·5 lbs.
Temperature of air before entering furnaces ...	260°	271°	—	220°	—
Temperature of gases at fan inlet	441°	393°	—	310°	—
Vacuum at fan inlet	3·5 in.	2·9 in.	—	1·75 in.	—
Vacuum over fires	1·1 in.	·8 in.	—	·2 in.	—

in transference of heat from these gases to the water. This, however, cannot be dealt with here.

In Patterson's plan[1] (Fig. 47) there is the addition of a spray of water which is injected into the fan for the purpose of keeping it cool, to prevent danger of warping, and to protect the mechanism generally. Beyond the results given by Mr. Paul in his paper, however, there does not seem to have been much done as yet with this plan.

Mr. Paul has recorded a consumption of coal in a return-tubular boiler at Levenford Works, Dumbarton, equal to 60 lbs. per square foot of grate per hour, with an evaporation of 15lbs. of water per square foot of heating surface in the same time, and

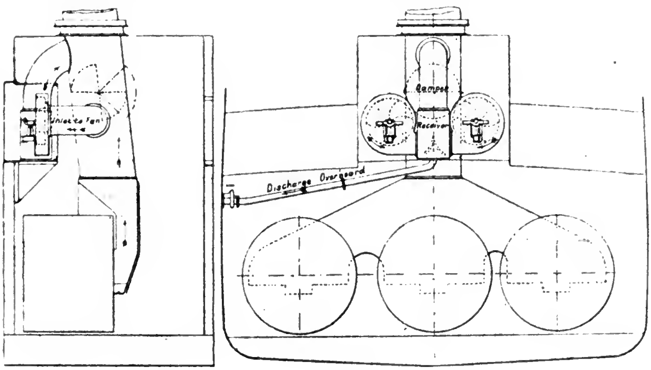


FIG. 47.

this is a very good result. It seems, however, to have been surpassed in the case of some of the Niclausse boilers in vessels of the French navy, in which the consumption of 80 lbs. per square foot of grate surface per hour has been recorded.[2]

Thornycroft Boiler.—The Table, at p. 552, Chap. IX., gives some results of trials of Thornycroft's water-tube boiler, with natural draught and with moderate air pressure in closed stokeholds, taken from Professor Kennedy's report, which accompanied Mr. Thornycroft's paper[3] on this subject. The following details are abstracted from the report referred to :—

[1] See "On Suction Draught," by Matthew Paul, Trans. Inst. Eng. and Shipbuilders in Scotland. Vol. xl.

[2] See *Engineering*, Jan. 1., 1897,. p. 11. "Memoires et Compte Rendu des travaux de la Soc. des Ingen. Civils de France." Jan., 1898. pp. 54-69.

[3] Min. Proc. Inst. C.E., Vol. xcix. 1890.

TABLE XIX.

	A.	D.	C.	B.	E.
Atmospheric pressure	14·80 lbs. per. sq. in.	14·55 lbs.	14·80 lbs.	14·84 lbs.	14·45 lbs.
Boiler pressure	186·0 lbs. per sq. in.	181·80	171·20 lbs.	149·40 lbs.	180·5 lbs.
Air pressure in stokehold above atmosphere	0·00	0·00	0·27 in.	0·49 in.	2·00 ins.
Air temperature in stokehold above atmosphere	—	69.3° Fah.	71·4° F.	60·3° F.	62·1° F.
Coal burnt per hour	334·0 lbs.	203·3 lbs.	559·0 lbs.	894·0 lbs.	1,751·0 lbs.
Area of fire grate	30 sq. ft.	26·2 sq. ft.	30 sq. ft.	30 sq. ft.	26·2 sq. ft.
Coal burnt per sq. ft. of fire grate per hour	11·10 lbs.	7·74 lbs.	18·60 lbs.	29·80 lbs.	66·80 lbs.
Feed temperature	78·4° F.	76·3° F.	78·00 F.	83·8° F.	111·2° F.
Water evaporated per lb. fuel	—	11·22 lbs.	10·48 lbs.	10·20 lbs.	8·89 lbs.
Equivalent evaporation from and at 212° Faht.	—	13·40 lbs.	12·48 lbs.	12·00 lbs.	10·29 in.
Temperature of gases in chimney	474° F.	421° F.	540° F.	610° F.	777° F.
Air pressure in chimney	0·00	0·00	+ 0·03 in.	+ 0·12 in.	+ 0·40 in.
Total heating surface	1,837 sq. ft.	1,837 sq. ft.	1,837 sq. ft.	1,837 sq. ft.	1,837 sq. ft.
Ratio of heating surface to grate	61·2	70·1	61·2.	61·2	70·1
Water evaporated per sq. ft. heating surface per hour ...	—	1·24 lbs.	3·20 lbs.	4·70 lbs.	8·50 lbs.
Mean rate of heat transmission per sq. ft. heating surface per hour	—	23·8 heat units.	61·0 heat units.	89 heat units.	158 heat units.
* Efficiency of boiler	—	86·8 %	81·4 %	78·2 %	66·6 %
Lbs. coal per I.H.P. per hour ...	2·220 lbs.	2·280 lbs.	1·981 lbs.	1·990 lbs.	2·260 lbs.

* The boiler efficiency is expressed in terms of the ratio between the actual evaporation and that theoretically due to the fuel calculated from analysis in the usual way.

Locomotive Results.—In the case of locomotive engines, with steam blast pipe in the chimney producing a powerful induced draught, a vacuum of seven to eighteen inches water column has, according to Mr. J. A. F. Aspinall,[1] been produced at the chimney end, three to seven inches in the smoke-box, and one to three inches over the brick arch in the fire-box. The mean of several trials registered a coal consumption of 60 lbs. per square foot of grate surface per hour, with a vacuum of three inches in the smoke-box, which corresponds with about one inch in the fire-box. An express locomotive, it has been said, burns, on an average, 100 lbs. of coal per square foot per hour. In general, the rate of combustion with forced draught seems to vary directly as the

[1] "Draught in Locomotive Boilers," by J. A. F. Aspinall, Proc. Inst. Mech. Engineers. 1893.

square root of the air gauge height, whether plenum or vacuum. Mr. M. Paul remarks, in the paper already referred to, that applying this rule to Mr. Aspinall's results, "it is found that with a vacuum of three inches in the fire-box, the coal will be burned at the rate of $60 \times \sqrt{3} = 105$lbs. per square foot of grate per hour, and this is confirmed by various authorities as a common performance in locomotive boilers." Mr. Paul adds, "With forced draught, a plenum of three inches is required for a coal consumption of 60lbs. per square foot of grate per hour, and for 105lbs. per square foot of grate a plenum of nine inches would be required, but this has not yet been reached."

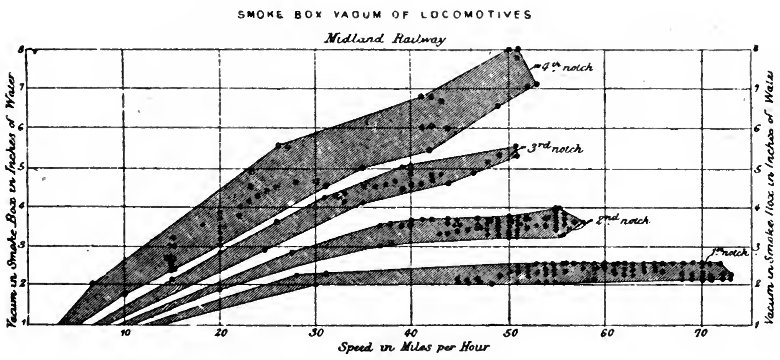


FIG. 48.

Air Pressure.—Regarding the amount of air pressure to be permitted in marine boilers, Mr. A. F. Yarrow[1] made the following remarks: "In the passage of the air from the stokehold to the funnel, the greater part of the resistance to be overcome in most cases is due to forcing the air through the tubes; consequently, if a contractor be limited to a given amount of air pressure, the only means he has to meet this condition without extra weight is by augmenting the diameter of the tubes, or reducing their length, thus producing rigidity, which I have already pointed out is bad. Because a certain boiler does not stand a given air pressure without the tubes leaking only proves that this air pressure is too much for that boiler, but does not prove that it is too much for every boiler, especially in view of

[1] Trans. Inst. N.A., vol. xxxii., p. 105.

the fact that locomotives are working all over the world at air pressures varying from three to eight inches.

"Fig. 48 shows the vacuum in the smoke-box of a Midland engine. This has been kindly given me by Mr. Johnson. In confirmation of the high air pressure used on locomotives, I quote the following statement of a locomotive superintendent of one of our local lines: 'We do not consider, from our experiments, that a vacuum of eight inches in a smoke-box is anything exceptional, but should expect it when working full power, either going up a bank or drawing a heavy train on a level. In addition to the vacuum in the smoke box we register a pressure of air in the front of the ash pan, due to the speed of the train, of two inches of water, making a total pressure of ten inches.' With these facts before us there ought to be no condition imposed upon the marine engineer limiting the air pressure."

Kemp's Feed Heater.—Before passing on to consider possible methods of improving the combustion in boilers, it is necessary to refer to the results obtained by the late Mr. E. Kemp in the application of feed-water heaters, wrought by means of heat in the waste gases, to marine boilers. He first commenced with a heater (Fig. 49) having a small proportion (about 3½ per cent.) of heating surface relatively to that of the boiler, but latterly had heaters (Figs. 50, 51) having over twice the boiler-heating surface, a distinct gain in temperature of the feed-water accompanying these additions to the surface of the heaters.

The system was tried with natural chimney draught (Fig. 49) and with forced draught on both the suction (Fig. 50) and the closed ashpit (Fig. 51) plans. The following Tables and Figs. give the particulars of the various vessels fitted and the resulting temperatures of feed water and of waste gases. Additional details will be found in Mr. Kemp's paper, "On Compound Marine Boilers." [1]

All the vessels named in Table I had the arrangement of apparatus shown in Fig. 49, with, however, an increase of surface in each succeeding case. The s.s. "Bléville" was fitted with the arrangement shown in Fig. 50, and the s.s. "Caloric" with that shown in Fig. 51.

[1] Trans. Inst. Eng. and Shipbuilders, Vol. xxxii., p. 201.

Table XX.

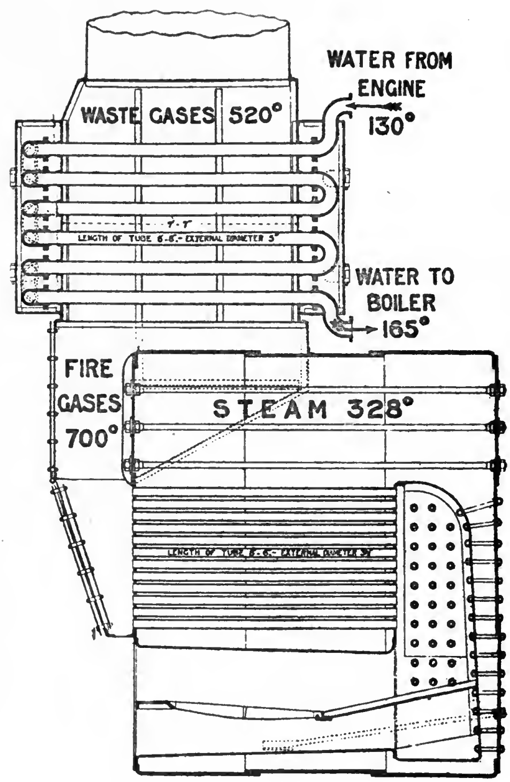
PARTICULARS OF MARINE BOILERS AND FEED HEATERS.

NAME OF STEAMER	WHEN BUILT	HEATING SURFACE IN BOILER	HTG SURFCE IN FEED HTR	FEED SURFCE TO BOILR SURFCE	TEMPR RAISED	FIRE GASES UTILISED	BOILER PRESSURE
		FEET	FEET		ABOUT	ABOUT	LBS.
"PLANTYN"	1879	3580	134	1 TO 26·6	15°	140°	80
"PIETER DE CONNINCK"	1881	5697	216	1 TO 26·4	15°	140°	80
"SORRINTO" "MARSALA"	1881 1882	3992	148	1 TO 26·9	16°	145°	80
"CLAN CAMERON" "CLAN CAMPBELL" "CLAN FORBES" "CLAN OGILVIE"	1882	4018	204	1 TO 19·68	20°	150°	85
"CLAN GRANT"	1883	5899	397	1 TO 14·85	25°	160°	85
"TAORMINA"	1884	3992	414	1 TO 9·64	35°	180°	80

PARTICULARS OF COMPOUND HIGH AND LOW TEMPERATURE MARINE BOILERS.

NAME OF STEAMER	WHEN BUILT	HTG SURFCE IN H.T. BOILER	HTG SURFCE IN L.T. BOILER	L.T. SURFACE TO H.T. SURFCE	TEMPR RAISED	FIRE GASES UTILISED	BOILER PRESSURE
"BLEVILLE"	1886	1768	3392	1·91 TO 1	150°	400°	160
"CALORIC"	1887	1613	3505	2·17 TO 1	140°	450°	160

Table XXI.


WATER FROM ENGINE
130°
WASTE GASES 520°
WATER TO BOILER
165°
FIRE GASES 700°
STEAM 328°

FIG, 49A.

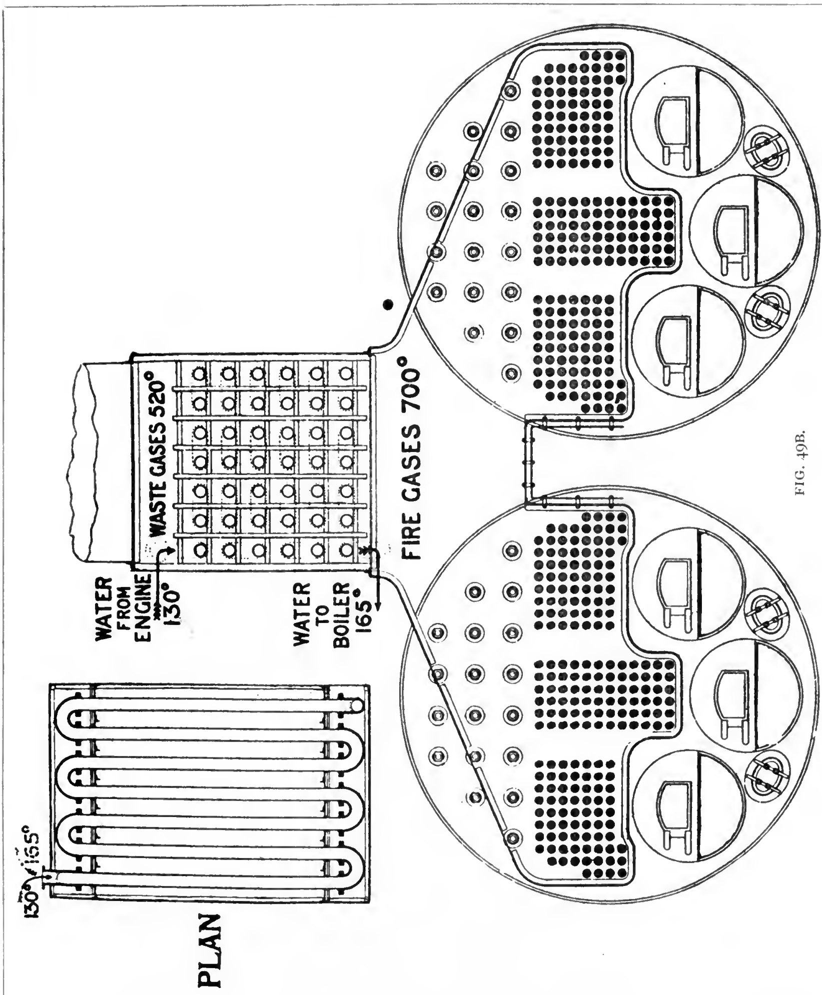

WASTE GASES 520°
FIRE GASES 700°
WATER FROM ENGINE 130°
WATER TO BOILER 165°
130°
155°
PLAN

FIG. 49B.

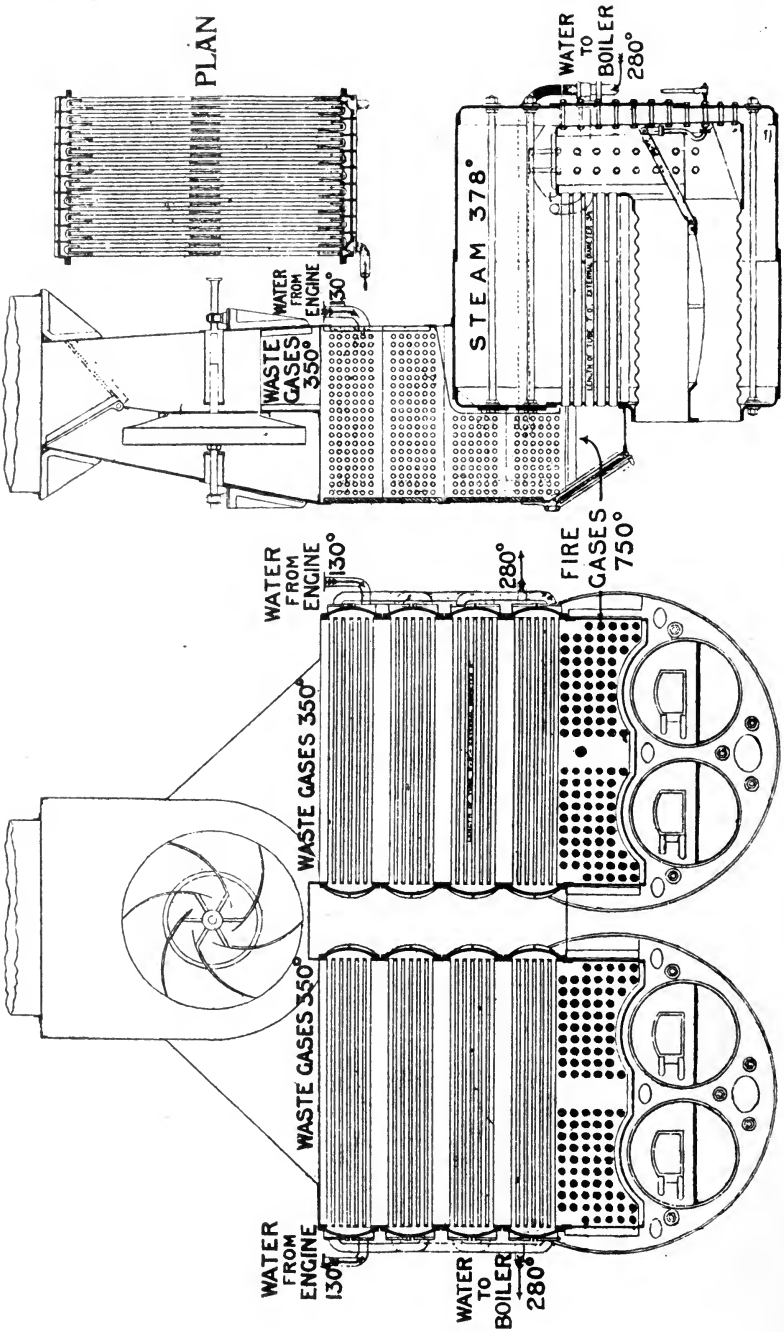

PLAN
WATER TO BOILER 280°
STEAM 378°
WATER FROM ENGINE 130°
WASTE GASES 350°
FIRE GASES 750°
WATER FROM ENGINE 130°
280°
WASTE GASES 350°
WASTE GASES 350°
WATER FROM ENGINE 130°
WATER TO BOILER 280°

FIG. 53.

Comparison of Air and Feed-heaters.—In discussing Mr. Kemp's results, Mr. Howden instituted a comparison between the feed-heater of the "Caloric" and the air heater which he had introduced into the "New York City," in order to prove that the heat-absorbing power of air is superior to that of water. The same view had already been expressed by Mr. Howden in his

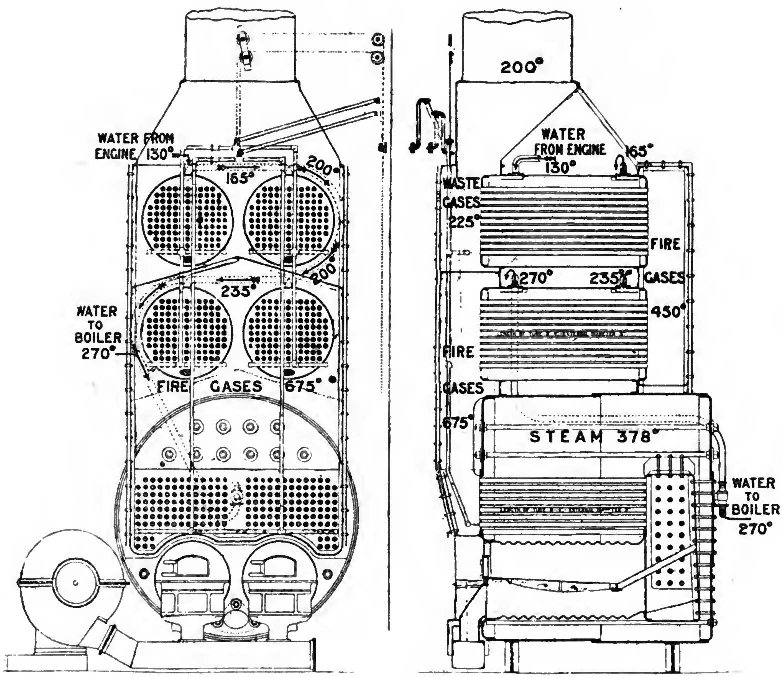


FIG. 51.

paper on "Forced Combustion in Furnaces of Steam Boilers" (Trans. I.N.A., 1886), in which he criticised some remarks made by Mr. J. T. Milton in his previous paper "On the Efficiency of Marine Boilers" (Trans. I.N.A., 1885). Mr. Howden said[1] "the boiler of the 'New York City' had a total heating surface of 1,597 square feet, that of the 'Caloric' being 1,613 square feet. Taking the coal consumed in the 'Caloric' as $9\frac{1}{4}$ tons

[1] Trans. Inst. Eng. and Shipbuilders in Scotland, Vol. xxxii., p. 213.

per day, as stated by Mr. Kemp, or 863½ lbs. per hour, and if for simplicity of calculation, the evaporation of water was taken at 10lbs. per lb. of coal, there were therefore 8,633 lbs. of feed water passing through the heaters per hour. The dimensions of these feed heaters, as given by Mr. Kemp, after deducting the space occupied by the 118 tubes in each heating vessel, left a capacity for 5,256 lbs. of water in each, and as 8,633 lbs. of feed water were supplied per hour, the time taken in passing through one feed-heating vessel was therefore 36½ minutes, and 2 hours 26 minutes in passing through the four heating vessels. In the boiler of the 'New York City' the air-heating chamber, through which the whole air for combustion passed, had a total heating surface of 225 square feet, and the capacity of the chamber was 16·8 cubic feet. The coal consumed on the trial, at which he was present and ascertained the results, was 1,030 lbs. per hour; and as 20 lbs. of air were used for combustion per lb. of coal consumed, the total weight of air passing through the heater per hour was 20,600 lbs. The temperature of the air on entering the heater was 70°, and on leaving 250°, so that the air was raised 180° in temperature in passing through the heater. The volume of air entering the heater was accordingly 13·4 cubic feet per lb., and on leaving 17·86 cubic feet per lb. As 20,600 lbs. of air passed through the heater per hour, 5·75 lbs., or 86·25 cubic feet passed through per second; and as the total capacity of the air-heating chamber was 16·8 cubic feet, it followed that the air-heating chamber was replenished 5·13 times every second, so that each particle of air was less than $\frac{1}{5}$ of a second in contact with the heating surface in passing through the heater. This gave, so far, the means of comparing the relative absorbent powers of air and water. In the 'Caloric' there were 8,633 lbs. of water raised 140° in temperature per hour by contact with 3,505 square feet of heating surface, but each particle of water had been in contact with or under the effect of the heating surface for 2 hours 26 minutes, while in the air-heater of the 'New York City' 20,600 lbs. of air per hour had been raised 180° by contact with only 225 square feet of heating surface, but where each particle had also only been in contact with the heating surface ·194 of a second. Putting aside, meanwhile, the time the air had been in the one case and the water in the other, under the heating power in their respective apparatus, and taking

the values of the specific heat of the 8,633 lbs. of water raised 140° per hour in the 'Caloric,' and of the 20,600 lbs. of air raised 180° per hour in the 'New York City,' their relative values are water 1, and air ·7178. The air was, however, increased in temperature by contact with only $\frac{1}{16}$ of the heating surface with which the water had been in contact, so that the air had absorbed 11·4 times more heat in the case of the 'New York City' than the water had in the 'Caloric' for equal areas of heating surface."

Such a comparison is, however, quite illusory, because of the enormous difference in the rates of movement of the particles, these being, according to Mr. Howden's figures, as 1 for the water to about 40,000 for the air. Mr. Howden evidently felt that it was not wholly satisfactory, as he added, that to test "the superior heat-absorbent powers of air over water" fairly, "equal weights of each should pass over equal surfaces under the same temperature in equal times." But even this would be misleading.

Heat Absorbing Powers of Air and Water.—The specific heats of water and air for equal weights, as determined by Regnault, are water 1·00, air 0·2374, so that the quantity of heat which would raise 1 lb. of air 1 degree, would raise 1 lb. of water only 0·2374°, or, in other words, water requires about four times the quantity of heat to raise its temperature that is required by the same weight of air. Nevertheless, it does not follow that air is necessarily raised in temperature more rapidly than water. Both are bad conductors, but still air is undoubtedly a much worse conductor of heat than still water. As in the case of all fluids, except perhaps mercury, heat is conducted through them almost wholly by convection, and freedom of movement is vital to convection. Where a comparison between the heat-absorbing powers of two fluids can be made is when both are outwardly quiescent, for then the speed of the action is dependent on the spontaneous or unassisted movement of their particles.[1] If the view that air is superior to water as a heat-absorbent were correct, air, instead of water, should be used as the circulating medium in surface condensers. But the largely increased surface required in air condensers, as compared with water condensers, bears witness to the relative values of the two as heat absorbers.

[1] See also C. Wye Williams on "The Combustion of Coal, etc.," pp. 164, 165.

In his experiments with air condensers, the late Mr. Thos. Craddock found that hot water in a metal tube, when immersed in still air, took twenty-five minutes to cool from 180° F. to 100° F., whilst in still water the same amount of cooling took place in one minute. When the tube was moved in the water at the rate of 3 feet per second, the rate of cooling was doubled, or half a minute sufficed for the loss of 80°. When, however, the tube was moved at the rate of 59 feet per second in air, the rate of cooling was 12 times that of still air, but was even then only about half the rate in still water.

In such vessels as the feed-heaters there is no large volume of water whose particles are free to move and set up convection currents in the mass, and consequently rapid movement from an extraneous source must be provided to take the place of natural convection. In the case of Mr. Kemp's feed-heaters this motion of the water was undoubtedly too slow for an economic result, but if the suitable rate of movement for maximum result with water were attained in them, it is probable that for an equal result, air would require to have a velocity at least 200 or 300 times as great. In the article "Heat" in "Encyclopædia Britannica," 9th edition, Sir Wm. Thomson gave the thermal conductivity of iron at 80 times, and that of copper at 500 times, that of water; and compared with air, he said that the conductivity of iron was 3,500 times, and that of copper 20,000 times, that of air—so that the thermal conductivity of water is over 40 times that of air.

Improved Methods of Combustion.—In order to effect improvement in the combustion department of marine and other boilers, attention must be given to the means for diminishing labour, for utilising the lower qualities of fuel, and for increasing the intensity of combustion. The conditions of work on board ship militate against the adoption of mechanical stoking arrangements such as are applied to the ordinary furnace grates on land. Moreover, there are strong reasons why such grates should be abolished. Putting aside mechanical stokers, we have the choice of firing with gas, firing with coal dust, or using external firing chambers with mechanical feeding. For gas-firing,[1] the intro-

[1] For gas-firing with boilers on land, see D. K. Clark, "The Steam Engine," Vol. i., p. 346; Mills and Rowan "On Fuel, etc."; Groves and Thorp's Technology, Vol. i., pp. 535–582; "Gas-Fired Boilers," Trans. Mining Inst. of Scotland, Vol. xi., 1889.

duction of gas producers on board ship is beset with difficulties, and the additional weight which they import into the machinery department is itself a strong argument against them. Apart from the use of gas producers, there is little chance of obtaining economical firing with gas, unless a really efficient method of quickly gasifying crude oils were worked out. The use of liquid fuel, by means of the ordinary arrangements for burning it in the form of spray, seems to be hopeless of any satisfactory prospect. As so used, twice the calorific value of good coal is scarcely ever reached, whilst the comparative cost of the fuel, at even that rate, quickly causes any monetary benefit to vanish.

Dust Fuel.—The use of powdered coal is more promising, especially in the forms introduced by Wegener, Schwartzkopf, Ruhl, De Camp, or Friedeberg, in Germany, which are modifications of the plan originally tried by Crampton. These plans are illustrated in the published Transactions of the Federated Institute of Mining Engineers, Vol. xi., Pl. 18, those of De Camp and Friedeberg being combined with an air-blast produced by a fan. A full description of them will be found in a paper by Mr. Bryan Donkin, Member of the Institute of Civil Engineers, in the Transactions of the Federated Institute of Mining Engineers, Vol. xi., p. 321. Refer also to *Engineering News* (New York), Vol. xlv., pp. 452, 453. They undoubtedly provide methods of complete and rapid combustion, without much excess of air, and without cooling of the boiler by frequent opening of furnace doors, but have drawbacks due to the necessity for the presence of coal-crushing machinery to grind the coal as it is used—as coal dust cannot, with safety and economy, be stored in bulk in the coal bunkers of steamships—and to the fact that all the ash of the coal is blown into the boiler furnace or casing, from which its removal must be attended with very great difficulty.

External Firing Chambers.—The use of external firing chambers has so much to recommend it that the only wonder is that they have not long ago been adopted. It is possible to use small coal or slack in them, and the fuel can be fed continuously by mechanical means of the simplest kind. The air, as well as the coal, is mechanically supplied, and there is no necessity for opening charging doors, so that the great causes of fluctuations in

temperature at the boiler surfaces are abolished, with the heavy labour of hand stoking.

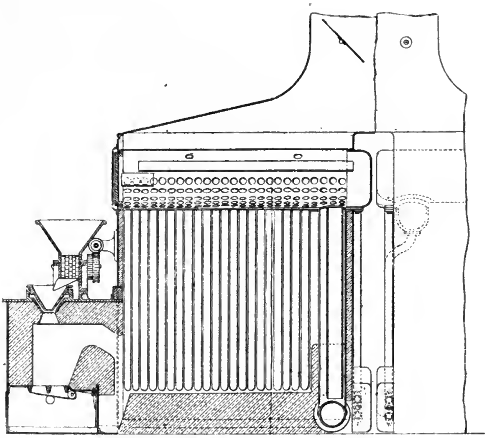


FIG. 52.

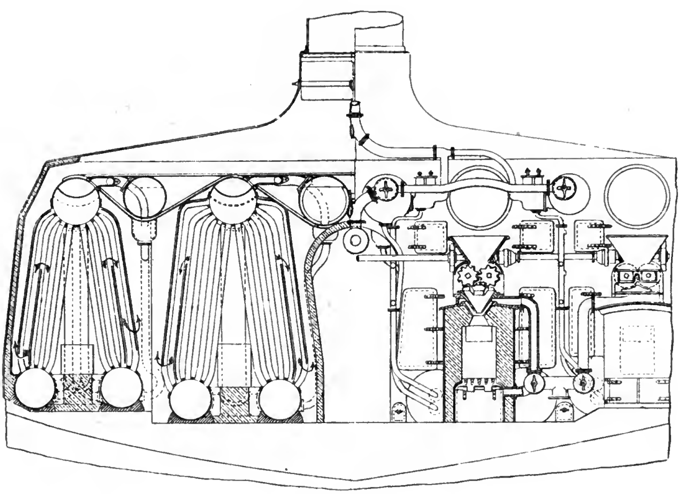


FIG. 53.

A plan which was proposed by the author in 1876 is shown in Figs. 52, 53. This combustion chamber was somewhat

similar in design to one invented by Herr C. Wittenström, of Stockholm, for the reheating furnaces of forges, and which acted fairly well when properly supplied with fuel.

Another plan, proposed by Captain Hamilton Geary in 1887, is shown in Fig. 54 (A and B). This furnace was devised principally for using anthracite in steam boilers, and succeeded well in the trials carried out in 1877 by Captain Geary.

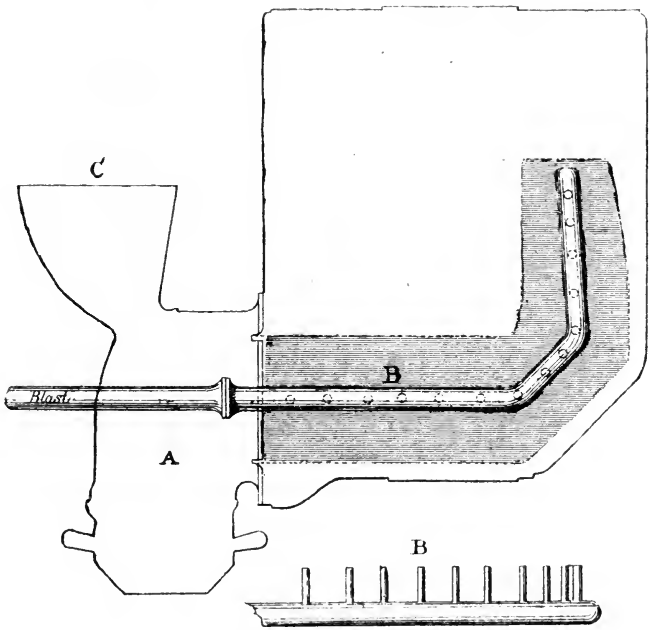


FIG. 54 (A AND B).

Although the advantages of an external firing-chamber for land boilers,[1] as regards completeness of combustion and absence of smoke, had long been known, nothing was done with these plans, and the system has still to be advocated as something new and as yet foreign to general practice, but certain in time to become necessary to the proper working of boilers.

Combustion under Increased Pressure.—The further step which must ultimately be taken in this department of the subject is

[1] See Mills and Rowan "On Fuel, etc.," pp. 513, 575–583.

that of conducting the combustion under considerable pressure. The pressures hitherto reached with the systems of forced or accelerated draught in use do not amount to more than 3 inches of water column in marine boilers and 8 to 10 inches in locomotive boilers, but these are a long way short of what will be required in the system here advocated. The *rationale* of combustion under increased pressure should be readily understood.

It was proved years ago, by Poisson and Laplace, that the specific heat of a gas maintained at constant volume is less than that of the same gas maintained at constant pressure, the difference between the two being caused by the quantity of heat which is rendered latent by the expansion of the gas. In other words, if a given weight of any gas is allowed to expand freely whilst it is being heated, a greater amount of heat is necessary to raise its temperature a given number of degrees than would be required for the same rise of temperature where the gas is maintained at a constant volume. It is clearly seen, that if a given volume of a gas which has been compressed or heated under any given pressure is allowed to expand to a lower pressure, its temperature will fall, and that a corresponding rise of temperature must accompany the opposite action.

The variation of the temperature of air under these conditions has been expressed by following formula :—

$$T = \left\{ (t + 461 \cdot 2) \times \left(\frac{P}{p} \right)^{0.29} \right\} - 461 \cdot 2$$

where

t = the temperature of the air in degrees F. at the pressure p
T = " " " " P.

The pressures P and p are measured above a vacuum and may be expressed either in atmospheres, lbs. per square inch, or any convenient unit of measurement. The $^{0.29}$th power of the fraction $\frac{P}{p}$ may be obtained by the use of logarithms. The specific heat of air when maintained at constant volume (*i.e.*, with *pressure* increasing) is 0·169 ; and when maintained at constant pressure (*i.e.*, with *volume* free to increase), 0·238, as compared with water as 1·0. Thus 1 lb. of air in expanding to the extent corresponding to a rise of temperature of 1° F., absorbs, or renders latent, 0·238 − 0·169 = 0·069 of a unit of heat.

When air is compressed, a sensible rise of temperature is noticed, which is due to the heat which has been employed in maintaining it in an expanded state becoming sensible. "In carrying on combustion under pressure the products are not first allowed to expand and then become heated by compression, but they are prevented from expanding as they would under ordinary circumstances, and, as far as effects go, the results are the same as if they were compressed. In other words, the temperature to be expected in a furnace working at a pressure of two atmospheres will be the same as if the products obtained by combustion under ordinary atmospheric pressure were, before becoming cooled, compressed to one half their volume." This rise of temperature may be calculated by the formula already given, taking for instance the temperature of the products resulting from combustion under atmospheric pressure at 2700° F. above the normal temperature of the air and fuel, which may be assumed at 60° F. The temperature of the products will in that case be 2760° F., and assuming, as we may without sensible error, that the formula for air is applicable to these gaseous products of combustion, the effect of conducting the combustion at a pressure of two atmospheres will be :—

$$T = \left\{ (2760 + 461{\cdot}2) \times \left(\frac{2}{1}\right)^{0.29} \right\} - 461{\cdot}2$$

$$= (3221{\cdot}2 \times 1{\cdot}222) - 461{\cdot}2 = 3475{\cdot}1^{\circ}$$

or a temperature 715° higher than that obtained from combustion carried on at atmospheric pressure.

By increasing the pressure to three atmospheres, a similar calculation will show that a further increase of temperature amounting to 493° may be expected.

A corroboration of the main facts here indicated will be found in the results of Regnault's investigations of the specific heats of gases, a *resumé* of which is given, under "Heat," in Watts' "Dictionary of Chemistry," Vol. iii., pp. 24–52 ; 81–136.

The effect of pressure in increasing the temperature of combustion has been illustrated in numerous experiments by Frankland,[1] who found that many flames which are non-luminous at ordinary atmospheric pressure become luminous

[1] See "Experimental Researches" ; also Jour. Chem. Soc., Vol. xvii. (1864), pp. 52-55 ; Brit. Assocn. Reports, Vol. xxxviii., p. 37 ; Proc. Royal Soc., Vol. xvi. (1868) ; Phil. Mag., Vol. xxxvi. (1868), pp. 309-311.

when exposed to considerable pressure. So general was this result found to be that Frankland deduced from it the principle that the luminosity of flames depends chiefly upon the density of the vapours formed by the chemical action of combustion, the temperature being affected in proportion. Further illustration of the subject is found in the high-pressure furnaces introduced experimentally in 1869 by Sir (then Mr.) Henry Bessemer, accounts of which will be found in *Engineering*, Vol. viii. (1869), pp. 197, 261, and in Proceedings of the Cleveland Institution of Engineers, 9th February, 1871, in a paper by Mr. W. H. Maw, from which some of the foregoing facts and arguments have been borrowed. Theoretically a limit is imposed upon the realisation of high temperatures of combustion by dissociation, but where heat is rapidly and continuously abstracted from flame, as is the case in steam boiler furnaces, it is very unlikely that the dissociation temperature of carbon dioxide could be maintained, if ever reached. Moreover, Bunsen's researches long ago showed that where oxygen is mixed with an inert gas, such as nitrogen, as is the case in atmospheric air, even where no *excess* of air is employed in combustion, such dilution lowers the possible temperature of combustion (as compared with what is possible with pure oxygen), so that a larger proportion of the combustible gas can enter into combination with oxygen on account of the action of dissociation being delayed. Bunsen showed also, that by successive undulations of temperature over a comparatively short range, successive quantities of gas enter into combustion, producing flame, and that thus a temperature very little short of the dissociation point can be maintained. On this subject there are some particulars in Mills and Rowan "On Fuel and its Applications." (Vol. i. of Groves and Thorp's Chemical Technology, pp. 366–368. See also "On Flame," Journal Society Chemical Industry, 30th March, 1889.)

In applying the method of combustion under high pressure to water-tube boilers it will, of course, be necessary to construct pressure-proof casings, but this does not offer any serious difficulty. In fact, this casing might form a feed-water heater. It would be desirable, also, to have an index of the amount of pressure existing in the combustion chamber from time to time,

[1] See also *Engineering*, Vol. xi., p. 181, etc.

and this could be readily afforded by the use of such a gauge as the ingenious one applied by Mr. Bessemer (See Fig. 55) to his high-pressure furnaces, or some modification of it.

It is evident from these considerations that the temperature produced in furnaces, and to which boiler surfaces are exposed, does not depend primarily upon the weight of air used per pound of fuel consumed, even when that combustion is judiciously effected, but upon the quantity of fuel brought under combustion in a given time and space—the greater the quantity consumed the higher being the temperature — and upon the pressure under which the combustion takes place.

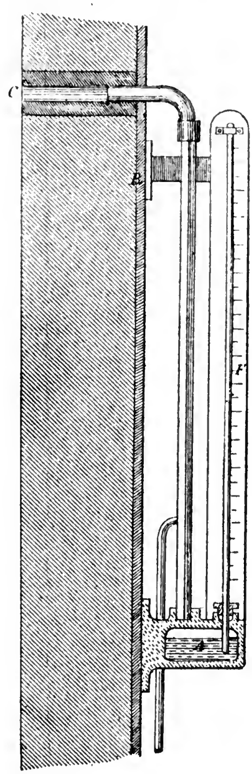


FIG. 55.

It follows from this that the proper basis for regulation of the area of uptake and flues is not the grate area, but is rather the weight of fuel which is burnt in given time, combined with the velocity with which the gases are made to travel in these passages. In fact, the main unit for the comparison or proportioning of boiler measurements is evidently the fuel; the heating surface being required in proportion to the number of heat units to be dealt with (derived from the combustion of the fuel and transmitted to the water), and the quantity of water being also in strict relation to that number. Further, the size of furnace or combustion chamber, and the quantity of air required, are directly dependent upon the weight of fuel to be burnt.

Progress is even now being made in the direction indicated in this chapter. Since it was written the following account of experiments in America has appeared in Trans. American Soc. of Naval Architects, a summary having been published in a daily paper (the *Glasgow Herald*, of October 19th, 1899). It records no mere trial of a mechanical stoker applied to the

ordinary grate of a marine boiler. Such an application has been made more than once in past times. It is clear from the account given that we have here the record of a serious step towards the introduction of a separate firing chamber, with mechanically fed fuel and possibly a higher degree of forced combustion than the ordinary one, and it is the possession of these features which gives such interest to the experiments recorded.

Considerable importance attaches to a series of tests made by the United States naval authorities with water-tube boilers using mechanical stokers, as it is recognised that automatic firing would confer enormous advantages in the direction of economy of fuel of poor quality, regularity of stoking, freedom from smoke, and reduction of stokehold staff. The results, which are very elaborate, are most promising. The vessel, a large steamer of 10,155 tons displacement, has two of Babcock and Wilcox water-tube boilers, supplying steam of about 250 lbs. pressure to quadruple expansion engines of about 1,600 indicated horse-power. The boilers have 5,000 square feet of heating surface, the weight being 65 tons, excluding water, which weighs 15 tons. Three mechanical underfed stokers are fitted to each boiler. Small coal thrown into a hopper is continually fed by a conveyor screw into a central magazine, and in this it is gradually forced upwards, overflowing the tuyere blocks, through which air is supplied by a blower. The coal is gradually heated as it is forced up in the magazine, and thus the volatile gases are released and are burned by the air issuing from the inside of the tuyere blocks. A sort of coke is at the same time furnished to the dead grates at the sides of the stoker, and the air for the combustion of this is supplied by the openings on the outside of the tuyere blocks. At the side of each stoker is a door for cleaning the grate, etc., and this could be utilised for ordinary stoking if the mechanism went wrong. No air is admitted except through the tuyeres. The weight of each stoker complete is 3,500 lbs. Inferior coal was used—a cheap grade of slack, the calorific value of a test sample having been 11,790 British thermal units per lb. when dry. The steam and water were measured for both main and auxiliary engines, and it was found that the six stokers used 138·6 lbs. of steam per hour, equal to 4·29 per cent. of the total steam generated ; but when the blower exhaust was passed through the feed heater the cost was only 1·68 per cent. of the total. The stoker worked satisfactorily in all tests—six trials each of six hours were made—and it was found that the main engines used on an average about 14·4 lbs. of steam per horse-power hour, and the auxiliaries 2·5 lbs. per hour per horse power of the main engines, the latter equal to about 14 per cent. of the total. The coal consumption for the main engines varied between 1·63 and 1·88 lbs., and for all machinery 1·9 to 2·20 lbs. The water evaporation averaged about 11 lbs. per lb. of coal from and at 212 degrees. These results, in view of the quality of coal, are most satisfactory, and the United States naval authorities have been impressed by the results ; but it is significant that they state that the steam consumption of the quadruple engine is not less than with triple-expansion.

CHAPTER IV.

Transmission of Heat.

The Steam Boiler a Heat-Engine.—The successful transmission of heat is the true solution of the greatest problem of boiler design. Several years ago it was shown that the proper light in which a boiler should be regarded is that of a heat-engine, to which the reasoning used in the case of all other examples can be applied. "The apparatus by means of which the potential energy of fuel, with respect to oxygen, is converted into the potential energy of steam, we call a steam boiler, and although it has neither cylinder nor piston, crank nor fly-wheel, I claim for it," said Mr. Anderson,[1] "that it is a veritable heat-engine, because it transmits the undulations and vibrations caused by the energy of chemical combination in the fuel, to the water in the boiler; these motions expend themselves in overcoming the liquid cohesion of the water and imparting to its molecules that vigour of motion which converts them into the molecules of a gas which, impinging on the surfaces which confine it and form the steam space, declare their presence and energy in the shape of pressure and temperature. A steam pumping-engine which furnishes water under high pressure to raise loads by means of hydraulic cranes, is not more truly a heat-engine than is a simple boiler, for the latter converts the latent energy of fuel nto the latent energy of steam, just as the pumping engine converts the latent energy of steam into the latent energy of the pumped-up accumulator or the hoisted weight." This is undoubtedly the true point of view from which to regard steam boilers in principle, and the application of this view reaches a good deal farther than any method of estimating the heat efficiency of boilers which has as yet been employed.

Heat Efficiency of Boilers.—The efficiency of a boiler is at present derived from the calculated evaporative power of the fuel, divided

[1] "On the Generation of Steam and Thermodynamic Problems Involved." Min. Pro. Inst. C.E., 1883-84.

into the actual evaporation obtained in lbs. of water per lb. of fuel consumed in the boiler, or in other words, the percentage of the calculated heat value in the fuel utilised in evaporating water into steam is made the basis of comparison of the heat efficiency of boilers. Mr. J. G. Hudson (in the *Engineer*, Vol. 70, page 449) takes the final efficiency E of a boiler, *i.e.*, the proportion which the heat utilised in raising steam bears to the full calorific value of the fuel expended, as the product of the separate efficiencies of the successive stages of the process. Thus :—

$$E_1 = \text{the efficiency of the combustion} = \frac{\text{the heat developed}}{\text{the calorific value of the fuel}}$$

$$E_2 = \text{the efficiency of the absorption} = \frac{\text{the heat absorbed}}{\text{the heat developed}}$$

$$E_3 = \text{the efficiency of the utilisation} = \frac{\text{the heat utilised}}{\text{the heat absorbed}}$$

$$\text{then } E_1 \times E_2 \times E_3 = E$$

and remarks that "under exceptionally favourable conditions the numerical values might be $E_1 = \cdot 96$, $E_2 = \cdot 93$, $E_3 = \cdot 97$, making $E = \cdot 866$; whilst more commonly they would be $E_1 = \cdot 90$, $E_2 = \cdot 75$, $E_3 = \cdot 95$, making $E = \cdot 641$, and much lower values are met with." He proposes to estimate E_2 by taking the weight and specific heat of the waste gases and their temperature in excess of that of the fuel and air as supplied to the boiler, and deducting that from the total heat developed. But this tells us nothing about the amount of heating surface which has been required in the boiler in the production of this result, and consequently (as the same rate of evaporation might be obtained from boilers having very different amounts of heating surface) it is not a good basis for comparison of various boilers. To obtain that we would require to have a proportion between the number of heat units which can, theoretically, be transmitted per unit of heating surface per unit of time, and the number actually transmitted in the case of any boiler, either per unit of surface or through the total heating surface in the boiler. The calculated heat value of fuel is by no means so exact or reliable an amount as is the number of heat units required to evaporate a given weight of water in given time, so that if we know the evaporative duty of

a boiler and its total area of heating surface, we can at once test its efficiency in terms of heat transmitted, that is, consistently with the view of the boiler as a heat-engine. It will, of course, be necessary to agree upon a standard, or the maximum amount of heat transmission which is theoretically possible per unit of surface, but this should not be difficult to do.

Carnot's Law.—The reasoning applied to heat-engines is founded on the law or principle announced first by Carnot,[1] that the ratio of the greatest possible work performed by a heat-engine to the whole heat expended is a function of the two limits of temperature between which the engine works, and not of the nature of the substance employed. It has been pointed out by several writers on physics that the greatest range of temperature possible is that which is measured on the absolute scale between the highest temperature at the commencement of the cycle of operations and absolute zero, and the fraction of this difference or range which can be utilised is the ratio which the range of temperature through which the substance is working bears to the absolute temperature at the commencement of the action.

If W = the greatest amount of effect to be expected, T and t = the absolute temperatures at beginning and end of the cycle, and H = the total quantity of heat potential in the substance at the higher temperature T, then the application of Carnot's law gives us the expression

$$W = H\left(\frac{T - t}{T}\right)$$

Illustration of Carnot's Law.—Mr. W. Anderson (in his lecture "On the Generation of Steam," etc.) gave the following graphic illustration of this doctrine: "Fig. 56 represents a hillside rising from the sea. Some distance up there is a lake, L, fed by streams coming down from a still higher level. Lower down the slope is the millpond, P, the tail race from which falls into the sea. At the millpond is established a factory, the turbine driving which is supplied with water by a pipe descending from the lake L. Datum is the mean sea-level, the level of the lake is T, and of the millpond t. Q is the weight of water falling through the turbine

[1] Réflexions sur la Puissance Motrice de Feu, Paris, 1824. Sir William Thomson, "Account of Carnot's Theory," Proc. Roy. Soc. Edin., Vol. xvi. (1849).

per minute. The mean sea-level is the lowest level to which the water can possibly fall, hence its greatest potential energy, that of its position in the lake, is QT=H. The water is working between the absolute levels T and t; hence, according to Carnot, the maximum effect W to be expected is

$$W=H\left(\frac{T-t}{T}\right)$$

but H=Q T, therefore $W=Q\,T\left(\frac{T-t}{T}\right)$

$$\text{and } W=Q\,(T-t)$$

that is to say, the greatest amount of work which can be expected is found by multiplying the weight of water into the clear fall,

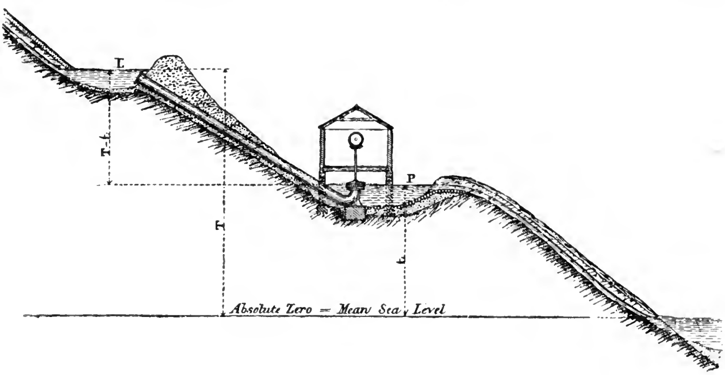


FIG. 56.

which is, of course, self-evident. Now, how can the quantity of work to be got out of a given weight of water be increased without in any way improving the efficiency of the turbine? In two ways :—

1. By collecting the water higher up the mountain and by that means increasing T.

2. By placing the turbine lower down, nearer the sea, and by that means reducing t.

" Now, the sea-level corresponds to the absolute zero of temperature and the heights T and t to the maximum and minimum temperatures between which the substance is working; therefore, similarly, the way to increase the efficiency of a heat-engine, such as a boiler, is to raise the temperature of the

furnace to the utmost, and to reduce the heat of the waste gases to the lowest possible point."

Methods of Increasing Range of Temperature.—We have seen in Chapter III how the temperature of combustion can be not only brought to, but also sustained at, the highest possible point, and, putting aside for the moment the question of the use of economisers and air heaters, the more complete the transmission of the heat to the water in the boiler can be made, the less will be the quantity of heat which can escape in the waste gases. Of course, the temperature due to the pressure of steam employed fixes a limit to the temperature of the escaping gases and therefore to this transmission, as far as the boiler proper is concerned, and it is at this point that the use of auxiliary apparatus comes in, so that a further amount of heat may be extracted from the waste gases or products of combustion.

As regards the transmission of heat, it is not necessary to discuss the refinements of the theory of the action described by Fourier (in his "Théorie analytique de la Chaleur"),[1] Poisson (in his "Théorie mathematique de la Chaleur"), Clerk Maxwell (in his "Theory of Heat"), and Lord Kelvin (in the article "Heat" in the "Encyclopædia Britannica," 9th Edition); we are more concerned here with its practical possibilities. Since the days of Sir Isaac Newton it has been known that, considering merely the metal medium, the rate of transmission is directly proportional to the difference of temperature between the two surfaces. This Newtonian principle was, in 1818, attacked by Dulong and Petit, who concluded, from a series of experiments on cooling in vacuo and in the atmosphere, that heat transmission took place more rapidly at higher temperature differences than at lower. The conclusion of these experimenters has, however, been corrected by subsequent investigation, and the general accuracy of Newton's view has been maintained. In fact, the early experiments of Dulong and Petit, Narr, Colding, and others, as well as many more recent ones on this and other allied subjects, seem to deserve the pithy remark of one writer, who says: "Whatever there can be said for or against the deductions of the experiments referred to, they

[1] There is an English translation of Fourier's work, by Freeman, published in 1879 at Cambridge University Press, 1 vol. 8vo.

all involve the same error, viz., that of deducing a law of universal application from too small a series of experiments, in which factors having an undoubted influence were omitted."

Great differences have been found in general practice, the average drift of which has been in the opposite direction to that of Dulong and Petit's conclusion, for, as we shall see, in the transmission of heat for evaporation, better results have been, so far, obtained with a difference of temperature of about 100° F. than with one of 1000° and upwards. The results obtained with steam boilers, and in various experiments connected with them, have in fact induced some engineers rather hastily to form the conclusion that the rule for boilers is that the rate of transmission of heat from the hot gases to the water, across the boiler plates or metal of the tubes, is proportional to the square of the difference of temperatures, in all cases. That boiler practice, however, has been far from embracing all the elements which can contribute to the best results possible, and the most of the experiments alluded to have been of a very partial and incomplete kind, except perhaps as regards the special form of apparatus experimented with in one or two instances. Some factors, such as for instance the absolutely essential and indeed commanding one of *the effect of movement*, have been either wholly or partially ignored in them.

Conduction of Heat.—The rule for the rate of conduction of heat by the metal itself seems to have been well ascertained. It is thus expressed by Professor Clerk Maxwell ("Theory of Heat," p. 234) :—

$$H = \frac{a\,b\,t\,k}{c}\,(T-S)$$

H being = the whole heat conducted in time t.
$a\,b$,, = ,, area of the plate.
c ,, = ,, thickness of the plate.
T—S being = the difference of temperature which causes the flow and
k being = the specific thermal conductivity of the substance.

"It appears therefore," Professor Clerk Maxwell says, "that the heat conducted is directly proportional to the area of the plate, to the time, to the difference of temperature, and to the conductivity, and inversely proportional to the thickness of the

plate." As to the dimensions of k, the specific thermal conductivity, he adds, "From the equation we find

$$k = \frac{c\ H}{a\ b\ t\ (T - S)}$$

"Hence if [L] be the unit of length, [T] the unit of time, [H] the unit of heat, and [θ] the unit of temperature, the dimensions of k will be

$$\frac{[H]}{[L\ T\ \theta]}$$

"If heat is measured in thermal units, such that each thermal unit is capable of raising unit mass of a standard substance through one degree of temperature, the dimensions of H are [M θ] and those of k will be $\left[\frac{M}{L\ T}\right]$"

Many similar expressions of this law or principle of heat conduction have been given, in which other symbols have been used, and perhaps the most convenient one is the following :—

$$Q = ks\frac{t - t^1}{e}T$$

Where Q is the quantity of heat which passes through a layer of the substance of thickness e, and area s, in time T, when its two surfaces are kept at the constant temperatures t and t' for a sufficient time to establish an even flow, k stands for the coefficient of conductivity.

Coefficient of Conductivity.—This coefficient of conductivity has been investigated by several experimenters, who have used principally three different methods or processes, the most direct of which is said to have been that employed by Péclet.[1] This consisted in "measuring the time required for a given quantity of heat to pass through plates of different materials of definite thickness, the two surfaces being maintained at known constant temperatures by keeping the two sides of the plate bathed with water."

Péclet's Experiments.—Péclet at first used a form of apparatus in which steam was employed as the source of heat on one side of a plate, whilst water was in contact with the other surface, over which it was moved by means of a rotating agitator. He

[1] Ann. Chem. Phys [3], ii. 107 and "Traité de la Chaleur," etc. Liége, 1844, chap viii. (3rd edn.)

noticed in all the experiments with this apparatus that the quantity of heat transmitted was sensibly affected by the speed of rotation of the agitator, increasing or diminishing in proportion to that speed, but the limit of speed of movement possible with the apparatus was too small. He therefore constructed a new apparatus, with the means of giving a greater movement to the water, which he now used on both surfaces of the plates, as he thought that a film of condensed steam in the previous apparatus probably interfered with the correctness of the results or with the rate of transmission. This new apparatus is shown in Figs. 56A, 57, and 58 in which Fig. 56A is a vertical section of the whole apparatus, Fig. 57 is a plan, and Fig. 58 a section (on an enlarged scale) of the bottom of the upper cylinder or vase, showing the plate experimented with at EF. The water was agitated on the upper surface of the plate by the vertical paddle, and on the under side by the horizontal wheel RS, which was moved by means of the handle X. By means of this apparatus Péclet was able to renew the liquid in contact with the surfaces of the metal plate 1,600 times a minute, and he obtained for lead plates the coefficient 3·84 in kilogram. water degrees for one square metre of surface, one millimetre of thickness, and one second of time, per 1° C. difference of temperature.

Taking, then, the numbers given by Despretz[1] for the relative conductivity of the different metals, Péclet gave the following Table of coefficients of absolute conductivity.

TABLE XXII.

Gold	21·28
Platinum	20·95
Silver	20·71
Copper	19·11
Iron	7·95
Zinc	7·74
Lead	3·84

Wiedemann and Franz's Results.—There seems, however, to be some reason to doubt this order, as later results given by

[1] These are given by D. K. Clark in "A Manual of Rules, Tables, and Data," p. 331, Table 107.

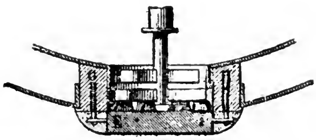


FIG. 58.

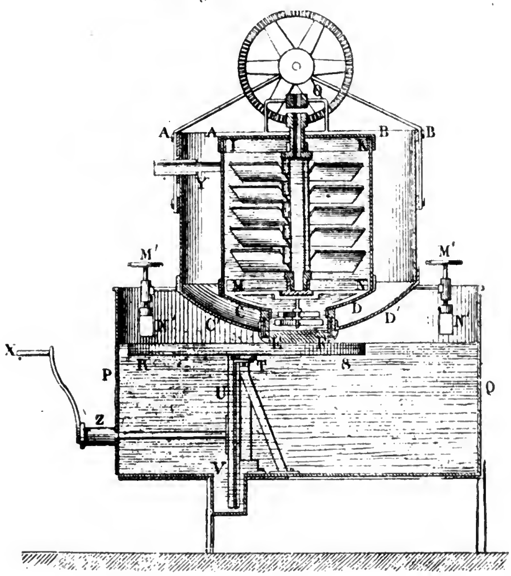


FIG. 56a.

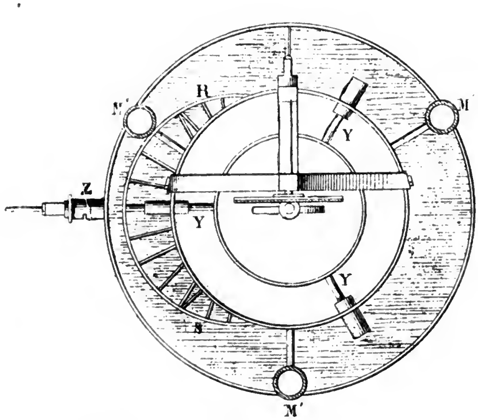


FIG. 57.

Wiedemann and Franz[1] (Pogg. Annal. lxxxix. 497), which are said to have been most carefully ascertained, present the relative conductivity of the metals in a different order of value. Their results are given in the following Table, the coefficients of absolute conductivity being calculated from these numbers on the basis of Péclet's result for lead, and expressed in gramme water degrees, per minute, per centimetre thickness, per square centimetre of surface :—

TABLE XXIII.

CONDUCTIVITY OF METALS.

	Relative.	Absolute.
Silver	100	45·2
Copper	73·6	33·4
Gold	53·2	24·0
Brass	23·1	10·4
Zinc	19·0	8·6
Tin	14·5	6·55
Iron	11·9	5·38
Lead	8·4	3·84
Platinum...	8·5	3·79
German Silver	6·3	2·85
Bismuth	1·8	0·81

Both Neumann[2] and Ängström[3] have also investigated the conductivity of metals, and have given the following results which have been reduced to expressions of absolute conductivity according to the same units at temperature $t°$.

In the column A the numbers refer to 1 gram. degree Cent. as the unit of heat, 1 centimetre as unit of length, and 1 minute as the unit of time. In column B the units are 1 kilogram. degree, 1 millimetre, 1 square metre, 1 second.

[1] See also Watts' Dict. of Chemistry, Vol. v., p. 71.

[2] Ann. Chem. Phys. [3] lxvi., 185.

[3] Pogg. Ann. cxiv. 527 ; cxviii. 429, see also Watts' Dict. of Chemistry, Article "Heat," Vol. vi., p. 693.

TABLE XXIV.

	Ångström.		Neumann.	
	A.	B.	A.	
Copper ...	61·63 (1 — 0·00214 t) 58·94 (1 — 0·001519 t)	102·7 (1 — 0·003567 t) 98·23 (1 — 0·002532 t)	66·48	110·75
Zinc ...	... ...	... ...	18·43	30·70
Brass ...	... ...	... ...	18·12	30·19
Iron ...	11·927 (1—0·002874 t)	19·88 (1 — 0·00479 t)	9·82	16·37
German Silver	... ...	... ...	6·57	10·94
Lead ...	(A) 2·30 (B) 3·84	Péclet.		

Mr. D. K. Clark[1] calculated from Péclet's Table, (XXII., on page 116) into English measures, the quantities of heat transmitted from water to water through plates of metals 1 inch thick, per square foot, for 1° F. difference of temperature between the two faces, per hour.

His figures are given in the following Table.

TABLE XXV.

Substances.	Quantity of Heat in Units.
Gold	620
Platinum	604
Silver	596
Copper	555
Iron	225
Zinc	225
Tin	177
Lead	112

Mr. Clark quotes the following formula from Péclet to express

[1] A Manual of Rules, Tables, Data, etc., 3rd edn., page 460.

the law of transmission of heat through metals (or other substances) :—

$$M=(t-t^1)\frac{C}{E}$$

in which t and t^1 are the temperatures of the surfaces, C the quantity of heat transmitted per hour for one degree difference of temperature through 1 unit of thickness, and E is the thickness. Table XXV. gives the values of the constant C for different metals in English measures.

Lord Kelvin (then Sir William Thomson)[1] has, however, shown that the figures given by Péclet and the earlier experimenters before Ängström, as expressing the conductivity, were in several instances too small ; those for the conductivity of copper, for instance, having been 200 times too small as given by Clement, and five times too small as given by Péclet.

Motion Essential to Transmission.—In considering the transmission of heat through metal plates to or from a gas, Péclet insists on the necessity for movement of the particles in contact with the heating surfaces for giving or receiving heat. In his own words : "Ainsi l'on voit que, dans tous les cas, le renouvellement rapide des couches de liquide ou de gaz qui touchent les surfaces de la plaque métallique a une trés-grande influence sur la transmission de la chaleur, mais que cette circonstance est beaucoup plus importante pour les gaz que pour les liquides. On doit donc chercher la disposition des appareils qui favorise le plus possible ce renouvellement, par l'effet seul du mouvement qui résulte de l'echauffement et du refroidissement, et par les mouvemens que les fluides doivent prendre pour entrer et sortir des appareils. Mais, pour les gaz, ou peut en outre produire artificiellement dans leurs masses des mouvemens qui occasionnent un renouvellement rapide des couches en contact avec les surfaces métalliques, soit par une action directe qui n'exigerait qu'un faible travail, soit en enployant une partie de la force qui résulte de l'coulement."

Direction of Currents.—In addition to this necessity for rapid motion, it is also plainly necessary, as Péclet indicates, that for a complete exchange of temperature the currents of the heating and heated fluids should be caused to move in opposite

[1] See article "Heat" in Encyclopædia Brit., ninth edition.

directions. By this method at all points of the travel of the heating medium its temperature must be higher than that of the substance being heated, so that transmission can always take place and all the heating surface can be made useful. When both currents traverse the surface in the same direction, they can only reach a mean temperature, which is soon attained, after which the heating surface is of no use.

In Chap. III. (pages 97–100, *ante*) two illustrations of the effects of movement (in one of the insufficiency of the amount of movement) on transmission of heat by air and water have been given, viz., in the case of feed-water and air heaters of Mr. Kemp and Mr. Howden, and in the case of Mr. Craddock's experiments with air and water condensers. The effect of movement is illustrated in Mr. Kemp's apparatus in the fact that his feed-water heaters required to have double the heating surface of his boilers in order to heat the slow moving water from 130° to 270°, the hot gases being cooled from 675° to 225°, the temperature of steam in the boiler being 363·4°; no steam was raised in the feed heaters, but to do this work the boilers required only half the surface of the heaters and only the movement of the water in the boilers can account for a great part of the difference. There is no doubt, however, that the higher temperature of the hot gases in contact with the boiler surfaces would also assist the more rapid transmission of heat.

Professor O. Reynolds on Heat Transmission.—In 1874 Professor Osborne Reynolds made a short communication to the Manchester Literary and Philosophical Society "On the Extent and Action of the Heating Surface for Steam Boilers," in which he directed attention to the influence of motion on the transmission of heat; and on account of the importance of the arguments advanced, this paper deserved to be more widely noticed than has been its fate. Professor Reynolds pointed out that in many of the works dealing with heat transmission "there is one assumption which upon the face of it seems to be contrary to general experience, and this is that the quantity of heat imparted by a given extent of surface to the adjacent fluid is independent of the motion of that fluid or of the nature of the surface; whereas the cooling effect of a wind compared with still air is so evident that it must cast doubt upon the truth of any hypothesis which does not take it into account." Accordingly, he approached the

subject on the side of the then recent laws of the internal diffusion of fluids on the molecular theory and thus stated his position: "The heat carried off by air or any fluid from a surface, apart from the effect of radiation, is proportional to the internal diffusion of the fluid at or near the surface; *i.e.*, is proportional to the rate at which particles or molecules pass backwards and forwards from the surface to any given depth within the fluid. Thus, if AB be the surface and *ab* an ideal line in the fluid parallel to AB, then the heat carried off from the surface in a given time will be proportional to the number of molecules which in that time pass from *ab* to AB, that is, for a given difference of temperature between the fluid and the surface. This assumption is fundamental to what I have to say, and is based on the molecular theory of fluids.

"Now, the rate of this diffusion has been shown from various considerations to depend on two things:—

"1. The natural internal diffusion of the fluid when at rest.

"2. The eddies caused by visible motion which mixes the fluid up and continually brings fresh particles into contact with the surface.

"The first of these causes is independent of the velocity of the fluid; if it be a gas is independent of its density, so that it may be said to depend only on the nature of the fluid.[1] The second cause, the effect of eddies, arises entirely from the motion of the fluid, and is proportional both to the density of the fluid, if gas, and the velocity with which it flows past the surface.

"The combined effect of these two causes may be expressed in a formula as follows:—

$$H = At + B\rho vt \qquad (1)$$

where t is the difference of temperature between the surface and the fluid, ρ is the density of the fluid, v its velocity, and A and B constants depending on the nature of the fluid, H being the heat transmitted per unit of the surface in a unit of time.

"If, therefore, a fluid were forced along a fixed length of pipe which was maintained at a uniform temperature greater or less than the initial temperature of the gas, we should expect the following results.

[1] "The Theory of Heat," by J. Clerk Maxwell, chap. xix.

"1. Starting with a velocity zero, the gas would then acquire the same temperature as the tube. 2. As the velocity increased, the temperature at which the gas would emerge would gradually diminish, rapidly at first, but in a decreasing ratio until it would become sensibly constant and independent of the velocity. The velocity after which the temperature of the emerging gas would be sensibly constant can only be found for each particular gas by experiment, but it would seem reasonable to suppose that it would be the same as that at which the resistance offered by friction to the motion of the fluid would be sensibly proportional to the square of the velocity. It having been found, both theoretically and by experiment, that this resistance is connected with the diffusion of the gas by a formula :

$$R = A^1 v + B^1 \rho v^2 \qquad (2)$$

and various considerations lead to the supposition that A and B in formula (1) are proportional to A^1 and B^1 in (2). The value of v which this gives is very small, and hence it follows that for considerable velocities the gas should emerge from the tube at a nearly constant temperature, whatever may be its velocity. This is in accordance with what has been observed in tubular boilers as well as in more definite experiments.

"In the locomotive the length of the boiler is limited by the length of the tube necessary to cool the air from the fire down to a certain temperature, say 500°. Now, there does not seem to be any general rule in practice for determining this length, the length varying from 16 feet to as little as 6 feet, but whatever the proportions may be, each engine furnishes a means of comparing the efficiency of the tubes for high and low velocities of the air through them. It has been a matter of surprise how completely the steam-producing power of a boiler appears to rise with the strength of blast or the work required from it. And as the boilers are as economical when working with a high blast as with a low, the air going up the chimney cannot have a much higher temperature in the one case than in the other. That it should be somewhat higher is strictly in accordance with the theory as stated above.

"It must, however, be noticed that the foregoing conclusion is based on the assumption that the surface of the tube is kept at the same constant temperature, a condition which it is easy to see can hardly be fulfilled in practice.

"The method by which this is usually attempted is by surrounding the tube on the outside with some fluid, the temperature of which is kept constant by some natural means, such as boiling or freezing; for instance, the tube is surrounded with boiling water. Now, although it may be possible to keep the water at a constant temperature, it does not at all follow that the tube will be kept at the same temperature; but, on the other hand, since heat has to pass from the one to the other, there must be a difference of temperature between them, and this difference will be proportional to the quantity of heat which has to pass. And again, the heat will have to pass through the material of the tube, and the rate at which it will do this will depend on the difference of the temperature at its two surfaces. Hence, if the air be forced through a tube surrounded with boiling water, the temperature of the inner surface of the tube will not be constant, but will diminish with the quantity of heat carried off by the air. It may be imagined that the difference will not be great; a variety of experiments lead me to suppose that it is much greater than is generally supposed. It is obvious that, if the previous conclusions be correct, this difference would be diminished by keeping the water in motion, and the more rapid the motion the less would be the difference."

Experiments with Steam.—A large proportion of the earlier experiments on heat transmission were experiments on cooling, and those investigations which have had evaporation in view have usually been conducted with steam as the heating agent, so that we still require experiments with higher temperature differences and with apparatus more suited to the conditions of the inquiry than the small vessels which have been used by Hirsch, Blechynden, Bryant, and others.

Although there has necessarily been movement of a kind in all the experiments, yet the effect of increased rates of movement has not been much inquired into. Of the early experimenters, according to G. A. Hagemann, only Colding (whose treatise, dated 1864, is said to have proved the complete correctness of Newton's law) attempted to determine the influence of speed on cooling; and it is the absence of proper provision for anything but very restricted movement that greatly detracts from the value of the experiments of most of the later investigators. Colding reached only a

rough approximation to a law for the influence of currents. Hagemann,[1] however, carried out several series of interesting experiments, not on cooling, but made with experimental apparatus which was designed in view of the evaporation of sugar and other liquors at comparatively low temperatures.

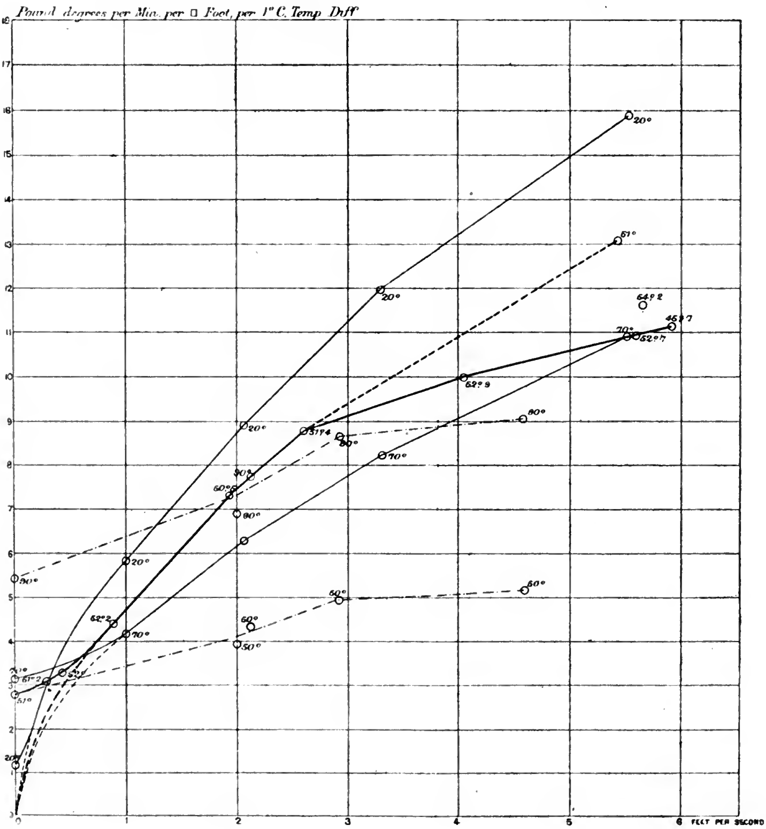


FIG. 59.

Hagemann's Experiments.—A series of experiments was undertaken to determine *the influence which speed of flow had upon transmission when the temperature-differences were constant* and the steam temperature was maintained at 100° C. The results are

[1] Min. Proc. Inst. C.E., Vol. lxxvii., pp. 311-322.

found in the following Table, marked 2A, and are graphically represented by the darker curve in Fig. 59, where the velocities of the water in feet per second are set off as abscissæ, and the corresponding heat-transmission as ordinates. The points shown by small circles were determined by measurement, and the points shown by large circles were borrowed from lines found by other experiments. A speed of 0, instead of giving no transmission, gave a very perceptible amount, which was caused by the streams generated in the water, the same circulation which renders possible a comparatively rapid heating of water, in spite of its being a bad conductor. At a temperature difference of 51° C., a speed less than that due to heating alone had but little influence, but with a greater speed the influence was very marked, the transmission increasing rapidly, though not quite in proportion to the speed.

After determining the influence of speed at a temperature difference of 51° C., another series of experiments was undertaken to find *the influence of temperature-differences at constant speed.* The results are marked 3, 4, 5 and 6 in the Table, and are graphically represented by the curves B, C, D. and E in Fig. 60.

The data for determining the first portion of the curves was wanting, but their form was assumed from other experiments and a comparison with the boiling or evaporation curve of the tube, which curve is shown at F.

From these results it appeared that heat-transmission per degree was greatest at low-temperature differences, but circumstances prevented the determination of the point at which maximum transmission was reached. Hagemann, however, supposed that the thermal conductivity of the heating surface under the conditions of his experiments was governed by the film of water which was constantly formed and renewed on the steam side of his metal tube. He was, no doubt, right in this, as Péclet had previously found that such conditions soon imposed a limit to heat transmission. Hagemann also undertook a series of experiments to investigate *the influence of speed of water on the heat transmission*, which, as he justly observes, is an important factor to be considered. The results of this series are given in the following Table, marked 8, 9, 10 and 11, with the curves G, H, I, and J, shown in Fig. 60.

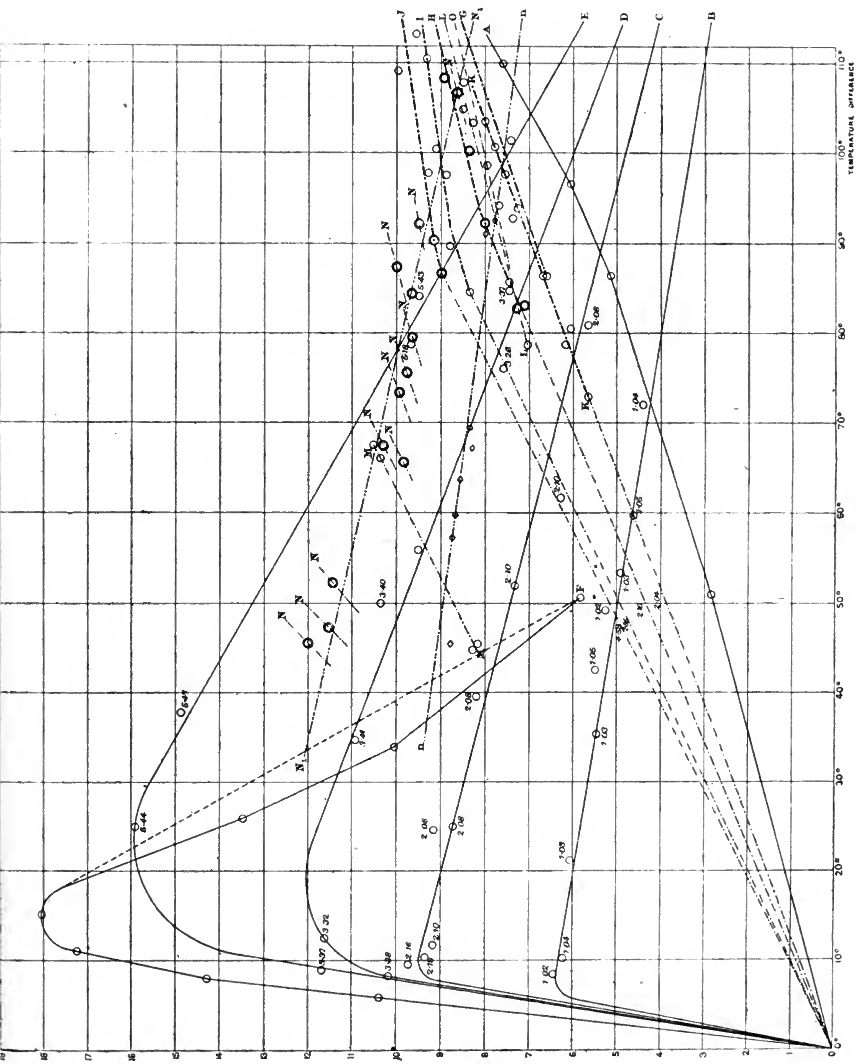


FIG. 60

Table XXVI.

8

HAGEMANN ON TRANSMISSION OF HEAT.

No. of Experiment.	Steam. Pressure in lbs. per sq. in.	Steam. Temperature Centigrade.	Water At Inflow.	Water At Outflow.	Temperature-difference.	Quantity of Water in lbs.	Time. Min.	Time. sec.	Heat-units transmitted per Minute.	Apparent Temperature-difference Centigrade.	Heat-units transmitted 1° Difference 1 Minute 1 Square Foot.	Velocity of Water in Feet per second.	Reference No. to Table and letter to Plate.
		°	°	°	°					°			
4	0	100	26·1	70·6	44·5	25·4	5	0	225·7	51·7	3·04	0·30	
5	0	100	25·8	70·7	44·9	25·4	5	0	227·5	51·8			
6	0	100	32·2	63·7	31·5	39·0	5	0	250·6	52·2	3·29	0·46	
7	0	100	32·2	63·4	31·2	38·6	5	0	240·7	52·2			
8	0	100	37·0	58·8	21·8	77·6	5	0	338·2	52·1	4·41	0·89	
9	0	100	36·8	58·7	21·9	72·3	5	0	316·6	52·1			
10	0	100	41·3	56·0	14·7	88·6	2	0	651·2	51·4	8·75	2·60	2. A.
11	0	100	41·2	56·0	14·8	86·9	2	0	643·8	51·4			
11*a*	0	100	41·3	52·9	11·6	101·4	1	30	757·9	52·9	9·99	4·06	
11*b*	0	100	42·8	51·4	8·6	95·7	1	0	826·0	52·7	10·94	5·57	
11*c*	0	100	41·2	50·5	9·3	113·5	1	10	904·7	54·2	11·65	5·67	
11*d*	0	100	50·7	58·0	7·3	99·6	1	0	729·7	45·7	11·14	5·93	
12	0	100	88·9	93·6	4·7	85·5	5	0	80·2	8·8	6·35	1·02	
13	0	100	86·4	92·0	5·6	85·5	5	0	95·7	10·8	6·17	1·02	
14	0	100	73·4	83·9	10·5	86·4	5	0	183·4	21·3	5·98	1·03	
15	0	100	56·8	72·7	15·9	86·4	5	4	275·0	35·3	5·43	1·03	
16	0	100½	47·8	66·9	19·1	87·5	5	0	334·0	42·7	5·45	1·04	3. B.
17	0	100½	40·0	61·4	21·4	69·9	4	0	368·1	49·3	5·19	1·02	
18	0	100½	35·5	57·3	21·8	86·4	5	0	377·1	53·6	4·90	1·03	
19	0	100½	28·9	51·7	22·8	85·3	5	0	389·5	59·7	4·55	1·02	
20	0	100½	15·9	41·7	25·8	87·5	5	0	452·1	72·2	4·36	1·04	
21	0	100	88·5	92·1	3·6	75·0	2	0	137·9	9·7	9·66	2·23	
22	0	100	88·0	91·7	3·7	73·6	2	0	136·0	10·2	9·29	2·19	
23	0	100	86·0	90·4	4·4	70·3	2	0	154·5	11·8	9·14	2·09	
24	0	100	70·5	79·8	9·3	70·3	2	0	326·6	24·9	9·14	2·07	
25	0	100	70·3	79·3	9·0	69·9	2	0	314·3	25·2	8·69	2·08	4. C.
26	0	100	55·1	67·8	12·7	69·9	2	0	443·5	38·6	8·17	2·08	
27	0	100	40·5	56·0	15·5	70·3	2	0	544·9	51·8	7·29	2·09	
28	0	100	30·7	46·2	15·7	70·5	2	0	553·8	61·7	6·22	2·10	
29	0	100	9·8	28·6	18·8	69·9	2	0	656·7	80·8	5·65	2·08	
30	0	100	90·8	93·0	2·2	56·6	1	0	124·6	8·1	10·14	3·35	
31	0	100	90·8	92·8	2·0	56·2	1	0	112·4	8·2			
32	0	100	85·4	89·2	3·8	65·0	1	10	211·8	12·7	11·59	3·31	
33	0	100	60·5	70·0	9·5	57·5	1	0	546·0	34·8	10·90	3·41	5. D.
34	0	100	43·5	56·5	13·0	57·1	1	0	741·2	50·0	10·34	3·40	
35	0	100	9·5	25·3	15·8	56·6	1	0	895·1	82·6	7·53	3·38	
36	0	100	89·7	91·4	1·7	90·4	1	0	159·2	9·5	11·68	5·38	
37	0	100	72·0	78·2	6·2	91·4	1	0	567·2	24·9	15·90	5·44	
38	0	100	52·8	61·6	8·8	107·4	1	10	809·0	37·8	14·91	5·46	6. E.
39	0	100	9·6	22·2	12·6	90·4	1	0	1,138·9	84·1	9·53	5·38	
40	0	100	9·6	21·5	11·9	77·2	0	50	1,102·3	78·9	9·66	5·50	

TABLE XXVII.

No. of Experiment.	Steam. Pressure in lbs. per Sq. In.	Steam. Temperature.	Water At Inflow.	Water At Outflow.	Temperature-difference.	Quantity of Water in lbs.	Time.	Heat-units trans-mitted per Minute.	Apparent Temperature-difference.	Heat-units transmitted 1° Difference, 1 Minute, 1 Square Foot.	Velocity of Water in Feet per Second.	Reference No. to Table and letter to Plate.
		°	°	°	°		Min. sec.		°			
56	0	104·4	5·5	30·8	25·3	99·2	3 2	826	86·2	6·67	1·94	8. G.
57	10	115·0	5·7	36·5	30·8	99·2	3 9	970	93·9	7·19	1·87	
58	20	124·0	5·6	40·2	34·6	99·2	3 11	1,071	101·2	7·37	1·83	
59	41	138·2	5·6	47·2	41·6	99·2	3 9	1,309	111·3	8·19	1·87	
60	0	100·4	5·8	29·2	23·4	99·2	2 46	844	82·9	7·07	2·14	9. H.
61	0	100·5	5·8	29·8	22·0	99·2	2 46	864	82·7	7·21	2·14	
62	8	112·8	6·0	35·4	29 4	99·2	2 47	1,060	92·1	7 98	2·14	
63	14	119·8	6·0	38·0	32·0	99·2	2 45	1,153	97·8	8·20	2·14	
64	16	122·5	6·0	39·0	33·0	99·2	2 45	1,190	100·0	8·30	2·14	
65	32	133·2	6·0	44·2	38·2	99·2	2 45	1,378	108·1	8·91	2·14	
66	0	100·5	6·0	26·2	20·2	99·2	2 0	1,003	84·5	8·30	2·95	10. I.
67	0	107·0	6·0	28·6	22·6	99·2	2 0	1,120	89·7	8·79	2·95	
68	11	116·0	6·0	31·0	25·0	99·2	2 0	1,239	97·5	8·83	2·95	
69	14	119·4	6·0	32·4	26·4	99·2	2 0	1,309	100·2	9·05	2·95	
70	29	131·5	6·0	35·8	29·8	99·2	2 0	1,477	110·6	9·27	2·95	
71	29	131·0	6·0	35·6	29·8	99·2	2 0	1,477	110·3	9·27	2·95	
72	0	100·0	6·4	20·8	14·4	77·1	0 59	1,111	86·4	8·91	4·59	11. J.
73	0	100·0	6·5	20·8								
74	0	105·0	6·8	22·2	15·4	77·1	0 59	1,188	90·5	9·14	4·59	
75	9	113·2	6·8	23·6	15·8	77·1	0 59	1,296	98·0	9·21	4·59	
76	22	126·0	6·5	26·6	20·0	77·1	0 59	1,543	109·1	9·89	4·59	
77	22	125·0	6·4	26·2								
78	28	130·5	6·3	26·6	20·3	77·1	1 0	1,565	113·6	9·48	4·59	
79	28	129·4	6·3	26·6								

He remarks on these curves, "It is a natural result of the method of experiment adopted, that the parts of the curves of transmission actually determined are not greater and begin rather high up, but *the principal result obtained previously,* namely, *that the transmission of heat increases with increasing speed, is further confirmed.*" These are amongst the most important of his results, and their value is certainly not lessened by the very sensible and modest remarks with which he closes his excellent paper. "The foregoing," he writes, "are the results of a series of careful experiments on some of the conditions affecting the heat-transmitting power of one form of heating surface, from which the experimenter hopes practical men may be able to obtain, at any rate, some little information. No attempt is made to deduce a general law from these experiments, owing to their

comparatively limited range, and to the neglect of several important factors, such as the form and position of the heating surface, the thermal conductivity of the metal forming it, and the specific heat of the liquid receiving the heat."

It would be well if all experimenters were able to take a similarly comprehensive view of the problems which they essay to solve. "Laws" and "rules" have often been hastily formulated on a much more slender basis of facts than those of Hagemann's careful experiments; no doubt under the mistaken notion that a "law" gives permanence to the experiments, instead of its being in epitome the ultimate truth of the subject investigated.

Nichol's Experiments.—Some good experiments on surface condensation of steam were carried out in 1875 by Mr. B. G. Nichol,[1] the condensing water having been passed through a brass tube $\frac{3}{4}$ in. diameter outside, which was enclosed in an iron pipe $3\frac{3}{4}$ in. diameter outside and $\frac{1}{4}$ in. thick, leaving a space of about $1\frac{1}{4}$ in. round the brass tube for the steam.

The condensing tube acted more efficiently in a horizontal than in a vertical position; a result said to be the reverse of what had been found by M. Clement when condensing in air.

The following are the velocities of the water through the tube in feet per minute, and the corresponding number of (British) heat units absorbed by the water per square foot of heating surface per hour, per 1° F. difference of temperature.

	Vertical tube.			Horizontal tube.		
Velocity	81	278	390	78	307	415
Heat units	346	449	466	479	621	696

The difference of temperatures of the steam and the condensing water were $255° - 58° = 197°$.

It appears from these experiments that the efficiency of the heat-transmitting surface was much increased by an increase in the velocity of the movement of the water. The velocity of the steam over the cooling surface is not stated. The brass

[1] See *Engineering*, December 10th, 1875.

tube had, however, a cooling surface of 1·0656 square feet, and the area of the steam space was 7·7640 square inches. The brass tube was 5ft. 5ins. long, and the weight of steam condensed per square foot of tube per hour was

52·32 | 78·18 | 84·34 || 67·8 | 104·6 | 121·3 lbs.

Professor Ser's Results.—Some systematic investigations of the effect of increase of velocity upon heat transmission have been made by Professor Ser[1] of the College of Arts and Manufactures in Paris, whose experiments have been utilised in connection with the evaporation of liquids[2] long before their bearing upon boiler practice was appreciated. In determining the effect of the rapid motion of water over the heating surface he used the following apparatus.[3] (See Fig. 61.) It consisted of a thin horizontal copper

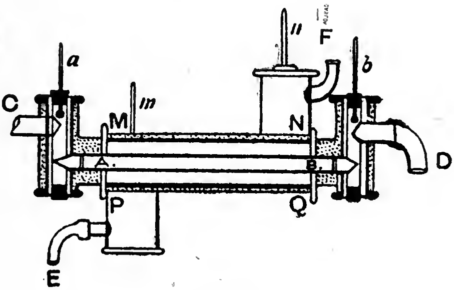


FIG. 61.

tube, A B, of a foot in length and four inches internal diameter, terminating at either end in a short length of vertical tube with a branch. The water entered at C, and flowing through A B, passed out at D, thermometers *a* and *b* being respectively placed in the vertical chamber at each end of A B to show the temperature of the water on entering and on leaving the tube. The tube A B was surrounded by a jacket or casing M N P Q, with branches similar to the end chambers of A B. This casing was also of copper, and the whole apparatus was covered with wadding to prevent radiation. Steam was passed into the casing

[1] *Traité de Physique Industrielle.* Vols. i. ii. Paris, 1887–1891.

[2] "Evaporation by the Multiple System," by James Foster. Second Edition, p. 562. Sunderland, 1895.

[3] "Halliday's Paper Inst. Marine Engineers," also "The Mechanical Engineer," Nov. 26, 1898, p. 786.

by the branch at E, and out at F, its temperature at entering and issuing being taken by thermometers at *m* and *n*. The temperature of the heating medium being constant, the effect of giving different velocities to the water upon the rate of heat transmission is shown by the following figures :—

TABLE XXVIII.

Speed of water through tube ; metres per second.	Coefficient of heat transmission.	Speed of water through tube ; metres per second.	Coefficient of heat transmission.
·1	1,400	·7	3,180
·2	2,230	·8	3,330
·3	2,550	·9	3,480
·4	2,710	1·0	3,640
·5	2,860	1·1	3,800
·6	3,020		

These results have been graphically represented by the following curve, and they deserve much attention, seeing that they were obtained in spite of the very short travel of the water through the tube A B, and also of the fact that the currents of both steam and water were passed in the same direction—both of these being conditions which militate against the most favourable result being obtained.

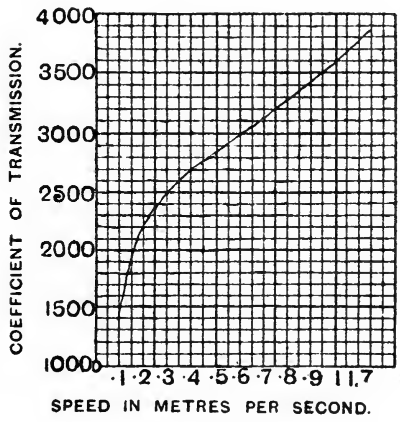


FIG. 62.

It is nevertheless evident that a considerable gain in efficiency of transmission is obtained by an increased speed of movement of the water over the heating surface, the curve rising steadily all the time, although more rapidly at the commencement, between the velocities of ·1 and ·3 metre per second.[1]

[1] Halliday's Paper, Inst. Marine Engineers.

Mr. G. Halliday[1] has observed that from the latter part of the curve—*i.e.*, from ·3 to 1·1 metre per second—the results yield the following calculation for coefficient of transmission :—

$$Q = 2{,}080 + 156 \times \text{velocity of the water},$$

which shows that the increase in efficiency is proportional to the velocity.

M. Ser has himself remarked that "the transmission of heat for the same difference of temperature is more than tripled when the liquid is boiling, which is due to the greater speed in the circulation of the heated liquid."

Now, the application of this fact to the natural motion of water when boiling is not the best, or by any means a final one ; although it may serve to show that certain water-tube boilers, or feed heaters, on account of the restricted size of their water channels or passages, must have a more rapid circulation, and therefore should give better results, than others. The question before us demanding a solution is not (or is only partially) what is the speed of circulation actually attained in any individual feed-heater, or boiler, or boiler-model ; but it is, what is the best speed for the water so that the greatest amount of heat transmission can be attained ? As far as M. Ser's results show, the speed may be increased much beyond his figures with correspondingly good effect.

Investigation, by the same experimenter, of the effect of motion on the transmission of heat to air or gases, yielded results showing advance in a similar direction. In this case, the experiments were carried out in tubes of ·25 metre in diameter, having fifty radial projections, or ribs, similar to those of a Serve tube. The height of these projections was ·05 metre, and they had a thickness of ·008 metre at their base, and ·002 metre at the top. The heating surface of each tube was 5·40 square metres, one being placed in a cylinder, or larger tube, leaving for the passage of the air to be heated an annular space of ·0488 of a square metre in sectional area ; the other tube was placed in a rectangular box, which gave a space round the tube for the air passage of ·098 square metre in sectional area—the area of the one passage was thus practically double that of the other.

[1] Trans. Inst. Marine Engineers, Vol. x, 77th Paper, p. 13.

The following are the results obtained :—

TABLE XXIX.

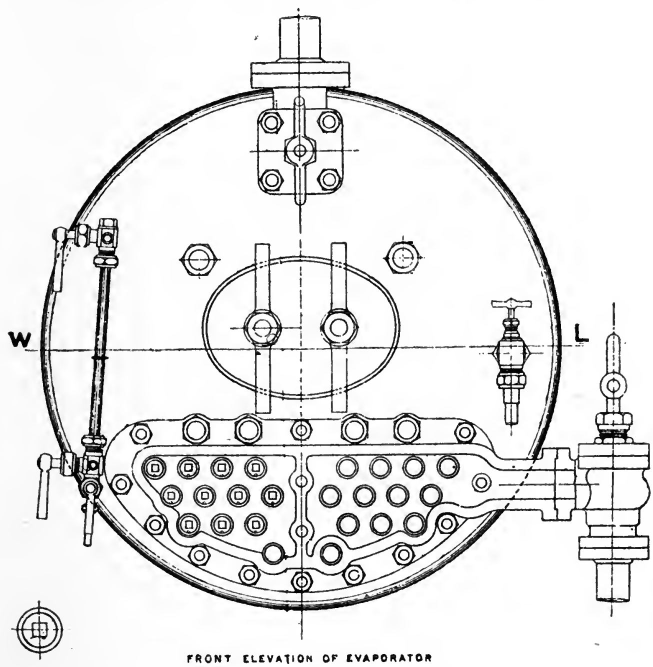
Sectional area of passage for air, ·098 square metre.		Sectional area of passage for air, ·0488 square metre.	
Speed through the passage in metres per second.	Coefficient in calories per square metre per hour.	Speed through the passage in metres per second.	Coefficient in calories per square metre per hour.
·42	4·80	1·137	6·8
·48	4·12	1·318	7·66
·57	4·82	1·350	7·74
·58	4·82	1·369	7·88
·65	4·88	1·648	8·56
·68	4·98	1·684	8·66
·75	5·06	1·884	9·42
·80	5·94	1·930	9·00
1·047	7·52	2·360	10·44

These results show that there is a decided advantage in increasing the velocity of travel of the gaseous body, and that the transference of heat increases in a greater ratio at the higher velocities.

C. R. Lang's Experiments.—Amongst the most interesting, and certainly the most successful, of experiments involving the transmission of heat from steam to water across metal, are those of Mr. C. R. Lang[1] on evaporation. Mr. Lang's experiments were carried out in a Weir's evaporator of the ordinary type, used to make ten tons of fresh water per day of 24 hours. It is shown in Figs. 63, 64, and 65. The shell consisted of a steel cylindrical vessel, 3ft. diameter by 4ft. 3in. long. The heating surface was composed of 12 solid-drawn copper tubes $1\frac{1}{2}$in. external diameter ($1\frac{1}{4}$in. internal diameter), giving a total heating surface of 38 square feet. The tubes were bent to the shape known as the "horseshoe" or **U** shape, and were arranged horizontally in the bottom part of the cylinder, in diagonal rows for convenience of scaling. The shape also gave a certain freedom of expansion without causing any strain upon the joints at the ends. The tubes were

[1] "On Evaporation," by C. R. Lang. Trans. Inst. Eng. and Shipbuilders in Scotland, Vol. xxxii., p. 287 (1889).

also arranged with Messrs. Weir's device of contracted ends and a return tube, this being an arrangement which in practice was found to cause the steam to pass continually and equally through all the tubes, preventing any lodgment of air or water in them to impair the efficiency of the surface, whilst the return tube carried off all the condensed water; and any steam which passed uncondensed through the contracted ends of the other



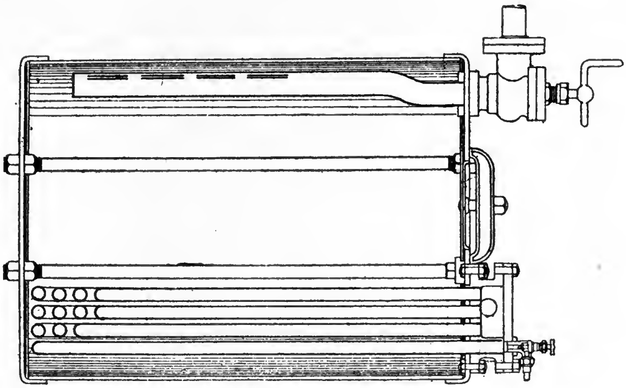
FRONT ELEVATION OF EVAPORATOR

FIG. 63.

tubes was condensed in it. The experiments were carried out in seven distinct sets of three to five different experiments, with a different initial steam pressure in the tubes for each set, the steam pressure in the shell being raised through each set. The first three sets were carried out with the full amount of heating surface, but it was found that at higher pressure the supply of steam from the boiler was inadequate, and in the last four sets the surface was reduced to 21·95 square feet by plugging up

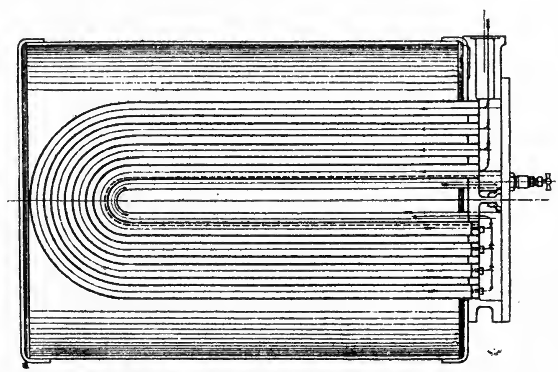
both ends of five of the tubes. Salt water, having a density of 19 oz. of salt to the gallon, was used in the evaporator. The steam evaporated from the salt water could be either led to a condenser or blown direct to the atmosphere.

Pressure gauges showed the pressures in the direct tubes, in



SECTIONAL ELEVATION OF EVAPORATOR

FIG. 64.



SECTIONAL PLAN OF EVAPORATOR TUBES

FIG. 65.

the return tube and in the steam space of the shell. The area of the 12 tubes at $1\frac{1}{4}$ in. internal diameter is 14·7252 square inches, and that of seven tubes of same diameter is 8·5897 square inches. On account of the bend in the tubes the velocity of the passage of the steam through them, which would be simply due to the difference of pressure, would be slightly diminished. It is

remarkable that the best results were obtained with the smaller amount of heating surface and the higher pressures of steam, causing a greater velocity of steam through the tubes in these experiments. In the cases of the first (A1) and the last (G4) experiments in the following table, the linear velocity of the steam was 14·9 feet per second, and 47·5 feet per second.

The results of the experiments are given in Table XXX.

Regarding this Table, Mr. Lang remarked, "Column 10 gives the actual weight of boiler steam condensed in the tubes per hour, taken by a weighing machine (Pooley's). The total heat given up by each pound of steam condensed in the tubes was plainly the difference between the total heat of the steam entering the tubes and the total heat of the water leaving the drain valve. Thus, let

Q = a quantity of steam condensed in tubes (in lbs. per hour).
S = total heating surface (in square feet).
H = No. of heat units given up per lb. steam condensed in tubes.
T = temperature of steam in tubes (in degrees F.).
t = " " shell "
L = latent heat of steam in shell.

Then the heat units transmitted per square foot of heating surface per hour $= \frac{QH}{S}$ (Column 14).

Lbs. water evaporated per square foot per hour

$$= \frac{QH}{SL} \qquad \text{(Column 15).}$$

Heat units transmitted per square foot per hour for 1° F. difference of temperature $= \frac{QH}{S(T-t)}$ (Column 16).

Lbs. water evaporated per square foot per hour for 1° F. difference of temperature $= \frac{QH}{SL(T-t)}$ (Column 17)."

The leading relations between these figures are shown graphically in various sets of curves, of which the specimen on page 143 is reproduced as bearing most directly on our immediate subject. In Fig. 66 the ordinates show the number of heat units transmitted per square foot of heating surface per hour for 1° F. difference of temperature, the abscissæ showing the number of degrees F. difference of temperature between the tubes and the shell.

TABLE XXX.

1	2	3	4	5	6	7	8	9	9A	10	11	12	13	14	15	16	17	17A
Series and No. of Experiment.	Absolute pressure. lbs. per square inch. Tubes.	Return.	Shell.	Temperature. Fahrenheit. Tubes.	Return.	Shell.	Weight of water condensed in tubes.	Time occupied.	Difference of temperature steam and water 5-7.	Lbs. water condensed per hour.	Heating surface in square feet.	Latent heat shell.	Heat units given up by 1 lb. steam.	Heat units transmitted per square foot per hour.	Lbs. evaporated per square foot per hour.	Heat units transmitted per square foot per hour for 1° F. diff.	Lbs. evaporated per square foot per hour for 1° F. diff.	Lbs. total water evaporated per hour. 11 × 15.
							lbs.	m. s.										
A. 1	29	28	23	248·4	246·4	235·5	56	9 37	12·9	349·39	38	948·5	942·7	8667	9·12	671	·707	
2	,,	26	20	,,	242·3	228	,,	5 16	20·4	637·9	,,	952·8	946·8	15891	16·67	779	·817	
3	,,	24	17	,,	237·8	219·6	,,	3 45	28·8	896	,,	959·8	951·3	22430	23·37	778	·811	
B. 1	35	34	29	259·3	257·6	248·4	,,	10 45	10·9	312·55	,,	939·4	934·9	7663	8·16	703	·748	
2	,,	31	24	,,	252·2	237·8	112	8 45	21·5	768	,,	946·9	940·3	19004	20·07	884	·933	
3	,,	28	18½	,,	246·4	223·5	,,	5 6	35·8	1317·6	,,	956·7	946·1	32804	34·28	916	·957	
C. 1	50	48	40	281	278·4	267·3	,,	16 42	13·7	402·39	,,	926	920·7	9749	10·53	711	·739	
2	,,	45	33	,,	274·4	255·9	,,	7 0	25·1	960	,,	934	924·6	23358	25	930	·996	
3	,,	41	22	,,	268·7	233·1	,,	3 8½	47·9	2138·9	,,	949·9	930·4	52343	55·10	1092	1·146	
D. 1	80	78	65	312	310·2	298	56	10 36½	14·0	316·73	21·95	904·2	898·3	12962	14·33	926	1·023	314·54
2	,,	75	56	,,	307·5	288·2	,,	5 22½	23·8	625·11	,,	911·2	901	25659	28·16	1078	1·183	
3	,,	65	35	,,	298	259·3	,,	2 11½	52·7	1533·07	,,	931·6	910·5	63592	68·26	1206	1·295	
4	,,	50	22½	,,	281	234·2	,,	1 32¼	77·8	2185·36	,,	949·9	927·5	92341	97·21	1187	1·249	2133·759
E. 1	105	102	75	331·3	329·1	307·5	,,	6 38	23·8	506·53	,,	897·5	885·3	20429	22·76	858	·956	449·58
2	,,	98	60	,,	326·3	292·7	,,	3 12½	38·6	1047·27	,,	908	888·1	42372	46·66	1098	1·208	
3	,,	90	50	,,	320·2	281	,,	2 20	50·3	1440	,,	916·3	894·2	58662	64·03	1166	1·273	
4	,,	74	40	,,	306·6	267·3	,,	1 48¾	64·0	1853·8	,,	926	907·8	76668	82·76	1198	1·293	
5	,,	62	33	,,	294·8	255·9	,,	1 33	75·4	2167·7	,,	934	919·6	90816	97.23	1204	1·289	2134·19
F. 1	135	124	75	350·1	343·6	307·5	112	5 18¼	42·6	1266·9	,,	897·5	876·6	50595	56·37	1187	1·323	1237·32
2	,,	111	60	,,	335·3	292·7	,,	3 42½	57·4	1812·13	,,	908	884·9	73054	80·45	1272	1·401	
3	,,	95	45	,,	324·1	274·4	,,	2 43½	75·7	2466	,,	920·9	896·1	100673	109·32	1329	1·444	2399·57
4	,,	81	30	,,	312·8	250·4	,,	2 10	99·7	3101·5	,,	937·9	907·4	128214	135·33	1286	1·357	2970·49
G. 1	165	150	85	366	358·3	316·1	,,	4 21¼	49·9	1543·3	,,	891·4	866·6	60930	68·35	1221	1·369	1500·28
2	,,	132	64	,,	348·3	296·9	,,	2 56	69·1	2290·9	,,	904·9	876·6	91489	101·14	1324	1·463	
3	,,	112	53	,,	336	284·7	,,	2 30½	81·3	2679	,,	913·6	888·9	108490	118·75	1334	1·460	2606·56
4	,,	92	35	,,	321·7	259·3	56	1 3½	106·7	3174·8	,,	931·6	903·2	130637	140·23	1224	1·314	3078

Several of the curves show graphically the facts set forth in column 16, by attaining a maximum height and then descending. Mr. Lang observed that "this seems to indicate that for each pressure in the tubes there is a corresponding pressure in the shell at which the efficiency of the evaporator is a maximum; and, further, that if we draw a curve which will be a medium between all the curves, the new curve will show the increase of efficiency of the evaporator as the difference of temperature increases. This curve is shown dotted in Fig. 66." It seems,

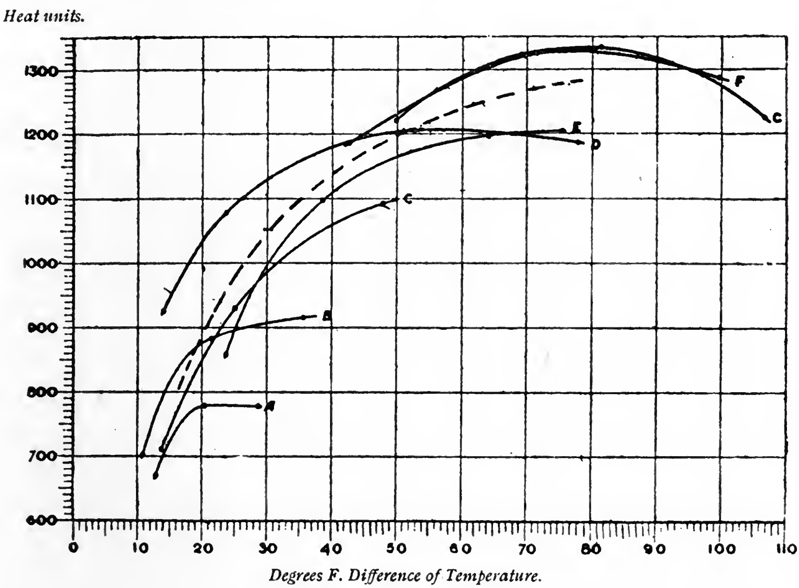


FIG. 66.

however, to be more likely that the transmission of heat was hindered beyond a certain point by the want of rapid circulation of the water in the shell. The shell contained about 885 lbs. of water, and in the various short periods through which the experiments extended, the actual quantity fed in would necessarily be small, because at the highest rate of evaporation attained, viz., 140·23 lbs. per square foot per hour, the total quantity required *per hour* would be 3,078 lbs., or little more than three times (about $3\frac{1}{2}$ times) the original quantity contained in the

shell. The circulation of the water would, therefore, be practically dependent only on the movement produced by the heat and steam in the water in the shell (*i.e.*, it would not be assisted by the introduction of colder feed water), and the arrangement of heating tubes is such as would not assist the descent of the water to the lower rows. It is in favour of the chance of freedom of circulation, however, that one side—the incoming side—of the **U** tubes is shown by the Table to have been some degrees hotter than the other side, and consequently the whole body of the water would tend to ascend at that side, and descend at the other side of the shell. Even at the best, however, it would not be very rapid movement, and it is more than likely that the efficiency of the evaporator was limited by the circulation. It was distinctly in favour of these experiments that the lower and higher degrees of temperature were thus properly applied in relation to the direction of movement of the water, so that the descending water was exposed to the lowest degree, and then the highest temperature and the ascending water met. This was, no doubt, what the apparatus adjusted itself to in the natural course of its action, but it was an element in its successful working. Had the movement of the water been made more rapid, probably a better result would have followed. Nevertheless, the results obtained with it have surpassed any others as yet obtained in transmitting heat from steam to water.

Mr. Lang justly remarks on this point: "On comparing our results with those previously obtained, we find that the best results hitherto published have been those of Péclet. Using a copper tube, 137·8 feet long, 1·36 in. outside diameter, made into a coil, with steam at 45 lbs. pressure admitted freely into one end of the tube, his highest result was 948 units of heat transmitted per square foot of heating surface per hour for 1° F. difference of temperature. In another experiment, using two coils of copper pipe, 52·5 ft. long, 1·36 in. diameter, he obtained a still higher result, viz., 1,120 units. These results have usually been looked upon as inaccurate, as being, in fact, too high, but on referring to column 16, it will be seen that not only have we reached the same figures, but that many of our results are a good way ahead of Péclet's, his highest result being 1,120, while our highest is 1,334."

The results of the experiments F No. 4 and G No. 4, although not the highest in point of number of heat units transmitted per degree difference of temperature, are most remarkable from the point of view of quantity of water evaporated per square foot of surface per hour, one showing 135·33 lbs. of water evaporated, where the temperature difference was 99·7° F., and the other 140·23 lbs. of water, with a temperature difference of 106·7° F. The results of D4, E5, F3 and 4 and G2, 3 and 4, form a remarkable series of evaporative results in connection with the subject of the utilisation of heating surface in steam boilers, and they ought to prevent any rash conclusions as to the rate of heat transmission in steam raising, based merely on trials of boilers or of apparatus, which, in the light of these results, should be acknowledged to be imperfect.

Experiments with Fire Gases.—We have now to consider experiments made with fire gases or flame as the heating medium, and it is at once manifest that we are here confronted with enormously greater temperature differences than those which have obtained in the experiments already considered. At the first glance we should therefore expect to see much *larger* results in heat-units transmitted and water evaporated per square foot of heating surface. Instead of that, however, we are face to face with the fact that, except in one or two experiments, the best results hitherto obtained have been far below those which, as we have just seen, are attained in practice in evaporation by means of steam. That is unfortunately the result in boilers considered as a whole, but these low results are undoubtedly due to the greater extent of heating surface which such boilers possess, in comparison with other apparatus, a great part of which surface is so used as to be very inefficient, whilst its presence reduces the apparent efficiency of the more useful portions. Evidence of this is to be found in the records of some early experiments with boilers which were, however, undertaken to ascertain only the manner in which the heat of the furnace was, as it was imagined, inevitably distributed over the boiler surfaces. Qualitative experiments were made by Robert Stephenson, Mr. Edward Woods, Mr. Dewrance, and others, including Mr. C. Wye Williams, a good account of which will be found in Mr. D. K. Clark's work on "The Steam Engine" (Vol. i. pp. 75–81). In general they all bore witness to a much more active evaporation

at the fire-box end of the boiler, which result was as generally ascribed solely to the action of radiant heat.

Graham's Experiments.—Mr. John Graham published in the Memoirs of the Literary and Philosophical Society of Manchester[1] the record of some careful experiments on the evaporative functions of steam boilers, which he had carried out in 1858. In the course of these he endeavoured to ascertain the proportion of the total evaporation which was due to different portions in the length of a cylindrical boiler, by dividing the boiler into sections of 3 ft. long, as in Fig. 67. The three cylinders were of plate $\frac{1}{4}$ in. thick, 3 ft. diameter, and 3 ft. long. They were placed end to end on a brick setting, so as to form practically a boiler of 9 ft. long. A grate 3 ft. long and 2 ft. wide was placed $9\frac{1}{2}$ in. below the first section, with a concentric flue of

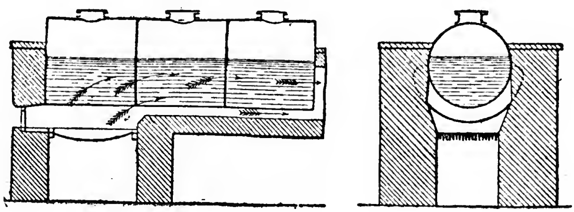


FIG. 67.

4 in. radial width, extending under the two succeeding cylinders, and carried up on each side to the level of their centres. The fire bars were $\frac{1}{2}$ in. thick, with $\frac{1}{2}$ in. air spaces, and the grate area was 6 sq. ft. The heating surface of the sections in their order from the grate end was 10·53, 14·13 and 14·13 sq. ft. respectively, making a total of 38·79 sq. ft. This is practically the same extent of heating surface as in the evaporator used in Mr. Lang's experiments, but no further comparison between them is possible, because the surface in Mr. Graham's boiler was so badly disposed for utilisation of the heat. The only point of interest in the results is that of the proportion of the total evaporation which is due to the various sections. The averages of numerous experiments showed that if the evaporation of the first were taken as 100, the second and third sections were represented by 39·3 and 17·1 respectively.

[1] Vol. xv. (1860), page 8.

A similar result was obtained in one series of Mr. Wye Williams' experiments, where he used a 6 ft. boiler and a 2 ft. boiler in different positions. When the 2 ft. boiler was placed second in the course of the hot gases from fire to chimney, it evaporated only 80 lbs. and 86 lbs. of water per hour, but when placed first it evaporated 417 lbs. per hour.

Northern Railway of France Experiments.—The most elaborate and useful experiments carried out on this part of our subject were undoubtedly those of the engineers of the Chemin de Fer du Nord (Northern Railway of France). The records of these experiments are found in writings of M. C. Couche[1] and M. Paul Havrez,[2] and in English in "The Steam Engine," by Mr. D. K. Clark.

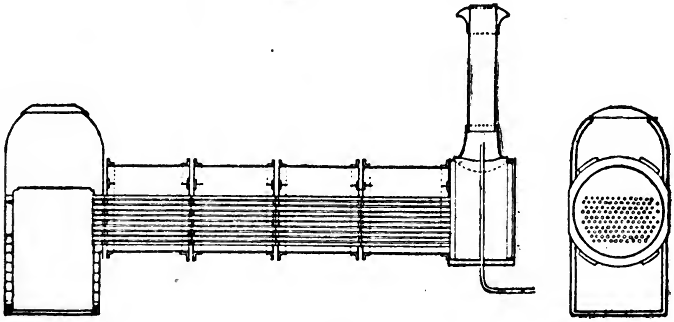


FIG. 68.

The boiler of a small goods engine was prepared for these experiments by being separated into five sections by the insertion of tube plates (see Fig. 68), the fire-box, with a small length of tubes ($3\frac{1}{2}$ in.), forming the first section. "The fire-box was 3 ft. square, presenting a grate area of 9 sq. ft., and a heating surface of 60·28 sq. ft. There were 125 tubes, 12 ft. 4 in. long, and about $1\frac{7}{8}$ in. in diameter. The barrel of the boiler with the tubes was divided into four sections, each 3·01 ft. in length. Each section, together with the fire-box portion, was closed at the ends by tube plates and made steam-tight, to be tried under steam of the

[1] Chemins de Fer, voie et material roulant, by M. C. Couche, 1876, Vol. iii., p. 32. Paris, Dunod.

[2] Annals du Genie Civil, 1874, p. 521; also Min. Proc. Inst. C.E., Vol. xxxix., 1875, p. 398, and "The Steam Engine," by D. K. Clark, Vol. i., pp. 84—90.

ordinary working pressure. The draught was excited by a blast of steam from another boiler." "The fire-box section contained 16 cubic ft. of water, and each tubular section held 11·3 cubic ft. Each section was fed from a gauged tank by a special donkey-pump, and the water levels were maintained strictly uniform. Each section was fitted with a steam chest, a pressure gauge, and a safety valve. The conditions of the trials were varied by plugging half the number of tubes." The heating surface was as follows :—

Heating surface.	Tubes all open.	Half tubes closed.
1st section (fire box 60·28, tubes 16·15)	76·43 sq. ft.	65·9 sq. ft.
2nd "	179 "	89·5 "
3rd "	179 "	89·5 "
4th "	179 "	89·5 "
5th "	179 "	89·5 "
Total surface	792·43 "	423·9 "

The total heating surface is equal to 88 times the fire-grate area.

The results of three series of these most interesting trials are given in the following Table. In the first and second series, coke and briquettes were the fuels used, and in the third series, with briquettes for fuel, half the tubes were closed by being plugged at the fire-box end. The force of draught was gradually increased in each series from 20 to 100 millimetres of water, measured in the smoke box. In regular work, the vacuum varied from 20 to 80 millimetres, or from about $\frac{3}{4}$ inch to $3\frac{1}{8}$ ins.

From the Table, it will be seen that "from two-fifths to one-half of the whole quantity of water was evaporated from the surface of the fire-box section, although this surface was less than one-tenth of the whole heating surface. Per square foot of the respective surfaces, the evaporation from the fire-box section amounted to from two to three times that of the first section of tube surface." The figures of quantity of water evaporated per square foot of heating surface in columns 7, 9, 11, 13, and 15, also show rates of from 20 to 44·7 lbs. obtained in the first section, with immediate falling off in the second and following sections, whilst the evaporation from the boiler as a whole—per square foot of heating surface—varied from 4·18 to 16·20 lbs.

TABLE XXXI.—ANALYSIS OF EVAPORATIVE PERFORMANCE OF LOCOMOTIVE BOILER. CHEMIN DE FER DU NORD.

I.—With all the Flue Tubes Open.

Fuel.	Force of Draught in Millimetres and Inches of Water.		Fuel consumed per hour.		Quantity of Water evaporated per hour from 60° F. into Steam of 80 lbs. per square inch.										Total.	
					First Section. Firebox.		Second Section. Tubes.		Third Section. Tubes.		Fourth Section. Tubes.		Fifth Section. Tubes.			
	Milli-metres.	Inches.	Total lbs.	Per sq. ft. of Grate. lbs.	Total lbs.	Per sq. ft. lbs.	Total lbs.	Per sq. ft. lbs.	Total lbs.	Per sq. ft. lbs.	Total lbs.	Per sq. ft. lbs.	Total lbs.	Per sq. ft. lbs.	Total lbs.	Per sq. ft. lbs.
Coke	20	.79	436.5	48.5	1,530	20.0	996	5.6	430	2.9	228	1.28	128	.72	3,312	4.18
	40	1.57	654.7	72.7	2,018	26.3	1,408	7.9	671	3.8	380	2.12	231	1.29	4,708	5.95
	60	2.36	727.5	80.8	2,222	29.0	1,789	10.0	931	5.2	528	2.96	337	1.88	5,806	7.32
	80	3.15	793.7	88.2	2,229	29.1	1,921	10.7	997	5.6	572	3.21	396	2.22	6,115	7.71
	100	3.94	771.6	85.7	1,810	23.6	1,892	10.6	1,030	5.8	614	3.44	484	2.47	5,786	7.30
Averages			676.8	75.2	1,962	25.6	1,601	8.9	812	4.5	464	2.59	315	1.76	5,154	6.48
Briquettes ...	20	.79	476.2	52.9	1,806	23.5	964	5.4	445	2.5	240	1.33	147	.83	3,602	5.98
	40	1.57	743.0	82.6	2,356	30.7	1,368	7.6	735	4.1	387	2.15	264	1.48	5,110	6.44
	60	2.36	923.7	102.6	2,933	38.2	1,969	11.0	1,025	4.5	645	3.61	425	2.38	6,997	8.82
	80	3.15	1025.0	113.9	3,291	42.9	1,778	9.8	920	5.1	579	3.24	422	2.36	6,990	8.81
	100	3.94	978.8	108.8	2,981	38.9	2,449	14.0	1,228	6.8	774	4.32	502	2.81	7,984	10.0
Averages			816.1	90.7	2,673	34.9	1,715	9.5	871	4.9	525	2.93	352	1.97	6,136	7.75

II.—With half the Flue Tubes Closed by Plugs at Firebox End.

Fuel.	Milli-metres.	Inches.	Fuel Total lbs.	Per sq. ft. of Grate. lbs.	First Section Total lbs.	Per sq. ft. lbs.	Second Section Total lbs.	Per sq. ft. lbs.	Third Section Total lbs.	Per sq. ft. lbs.	Fourth Section Total lbs.	Per sq. ft. lbs.	Fifth Section Total lbs.	Per sq. ft. lbs.	Total lbs.	Per sq. ft. lbs.
Briquettes ...	20	.79	388.0	43.1	1,811	26.5	803	9.0	356	4.0	191	2.09	117	1.31	3,278	7.75
	40	1.57	610.7	67.9	2,057	30.1	1,138	12.8	550	6.2	308	3.37	187	2.09	4,240	9.96
	60	2.36	707.7	78.6	2,710	39.6	1,448	16.2	722	8.1	449	4.90	290	3.24	5,619	13.20
	80	3.15	793.6	88.2	2,979	43.6	1,624	18.1	845	9.5	475	5.18	334	3.75	6,252	14.70
	100	3.94	848.8	94.3	3,058	44.7	1,874	21.0	948	10.6	580	6.34	425	4.76	6,886	16.20
Averages			669.8	74.4	2,523	36.9	1,377	15.4	684	7.7	400	4.38	271	2.99	5,255	12.34

The important fact is that a rate of evaporation amounting to nearly 50 lbs. of water per square foot of heating surface was obtained from a part of a boiler—and if from a part, why not from a whole boiler? Moreover, the Table conveys the significant fact that the rate of evaporation was greatly affected by the velocity of movement of the hot gases, as indicated by the varying force of draught used and the area of the flue tubes.

Thus, with briquettes for fuel, and all the flue tubes open, the figures were:—

Force of draught—millimetres	20	40	60	80	100
Evaporation in 1st section, lbs. per sq. ft. of surface ...	23·5	30·7	38·2	42·9	38·9

whilst with the same fuel and half the flue tubes closed, the figures for evaporation were, for the same draught pressure—

26·5	30·1	39·6	43·6	44·7.

The effect of reducing the flue-tube area by one half for the same draught pressures, would be to cause a more rapid rate of movement over the heating surface, and in those tubes which were open, and hence the evaporation in all the sections of the boilers was increased in the trial made under these conditions. The above are the figures for the first section of the boiler, but the evaporation in the other sections was increased in greater proportion.

Fig. 69 shows in a graphic manner the distribution of heat in the various sections of the boiler.

Hirsch's Experiments.—Some similar phenomena were shown in the results of experiments carried out by M. J. Hirsch,[1] at the Conservatoire des Arts et Metiers, at Paris—perhaps the most important as yet published. These experiments were divided into three parts, comprising :—

I. Investigation of the rate of evaporation in the part of a boiler most exposed to the heat of the fire and liable to overheating ;

II. Experiments on the transmission of heat through metal plates, from flame on one side to water on the other ; and

[1] Published in Annales du Conservatoire des Arts et Metiers, Paris, 2nd series Vol. i., and in Bulletin de la Société d'encouragement pour l'Industrie Nationale, 4th Ser., Tome v. (May, 1890), p. 302 ; also Abs. in Min. Proc., Inst. C.E., Vol. cviii., p. 464.

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III. A special study of the effects of a coating of oil or grease on the conductivity of the coated surface.

I. *Evaporation.* — In connection with the first part, M. Hirsch rightly pointed out that the figures usually given to express the rate of evaporation in boilers per square metre (or per square foot) of heating surface, are only averages obtained by dividing the total evaporation by the total area of surface exposed to the action of heat. They do not afford any idea of the actual intensity of evaporation at any one point, and yet it is well known that in the neighbourhood of the fire the rate of evaporation must be much greater than at other points farther removed from it. In no boilers hitherto made is there anything like a uniform rate of evaporation at all parts of the surface. Consequently, it becomes important to learn what is the maximum rate in those parts which are more directly subject to the action of the fire.

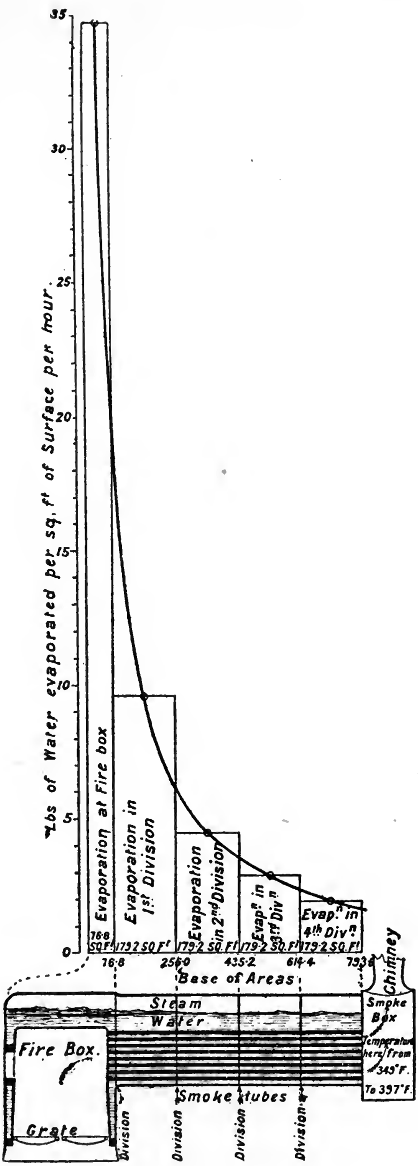

FIG. 69.

With a view to ascertain this, M. Hirsch took a cylindrical boiler 10 ft. long and 2 ft. 2 ins. diameter, with heating surface amounting to $35\frac{1}{4}$ sq. ft. There were horizontal feed-heaters added, with a surface of $107\frac{1}{2}$ sq. ft., so that boiler and feed-heater together had a total heating surface of $142\frac{3}{4}$ sq. ft.. The grate area was 3·85 sq. ft. and a blower was applied for the higher rates of combustion. A small portion of the surface of the boiler, directly over the fire, just in front of the bridge, was isolated by means of a vertical tube being bolted to the plates, a joint being made with asbestos and india rubber. The tube was of copper, 4 ins. diameter, and extended above the water level in

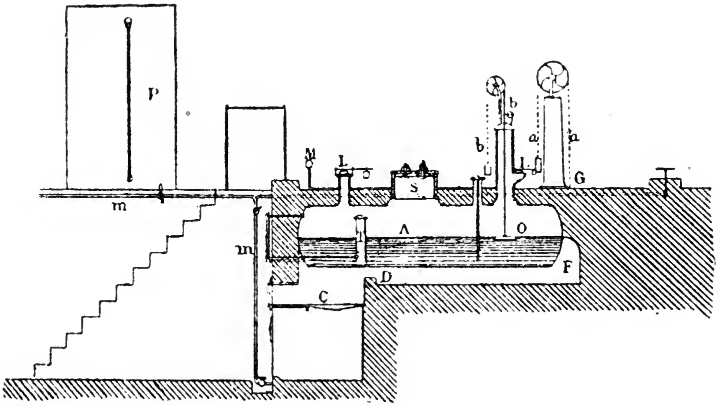

FIG. 70.

the boiler, with a cover to prevent its liquid contents being projected out of the tube, whilst the steam generated in it could escape into the steam space. The heating surface of the tube was 19·3 sq. ins.,[1] and it was separately supplied with water, which was maintained at the same level as in the boiler. Previous to an experiment, the boiler was heated for several hours and communication was then cut off between it and the experimental tube. During the trials the steam pressure was kept at about 60 lbs. per sq. in.

The arrangement of the apparatus is shown in Figs. 70,

[1] How this was arrived at does not appear in the paper, as the tube was heated entirely through the plate at its bottom end, and therefore the area of heating surface should apparently be 12·566 sq. ins., or a fraction over that.

71, and 72, in which A is the cylindrical boiler, C the grate, D the bridge, F the flues, L the safety valve, S the man-hole, T the experimental tube, and N the water gauge ; B B are the feed-heaters. In M. Hirsch's paper, the results of the experiments are tabulated, showing the total consumption of coal or coke and of water ; the consumption of fuel in kilogrammes per square metre of grate surface per hour, and the evaporation of water in litres per square metre of heating surface per hour (1) in the cylindrical boiler alone, (2) with the feed-heaters added, and (3) in the experimental tube.

With different degrees of force of draught and intensity of

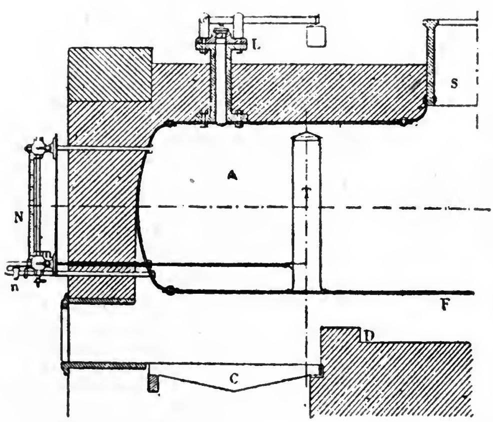

FIG. 71.

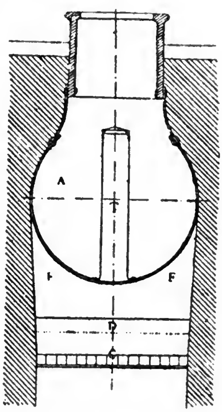

FIG. 72.

fire, the consumption of fuel per hour per square foot of grate varied from 16 lbs. to 48 lbs. M. Hirsch remarked that in general the evaporation in stationary boilers of this form ranges from 1·6 to 2·4 lbs. of water per hour per square foot of heating surface. In this boiler under (1), it ranged from 9·5 to 20 lbs. per square foot of surface per hour ; under (2), from 2·4 to 5·2 lbs. ; but under (3), in the tube covering the highly heated portion of surface, the rate of evaporation was from 21 lbs. to 50 lbs. per square foot per hour.

This is undoubtedly a good result, but it will be apparent, on examination of the sectional elevation of the boiler and tube, hat the experimental tube was of such a limited size and was

so arranged as to present great difficulties in the way of the proper circulation of the water in it, and consequently, that even a better evaporative result might have been obtained with a better arrangement. The heating took place only at one end of the tube, because when the water was boiling in both tube and boiler there could be no heating through the sides of the tube, all being at the same temperature, and all the circulation possible was that which could take place within the limits of the tube, the upward and downward currents having each to find a passage for itself. At the rate of evaporation noted, it is probable that the circulation could only have been pulsatory, the water finding its way down after each outburst of steam. Under the circumstances described it is remarkable that so high a rate of evaporation was attained. The presence of a concentric tube, or of some form of diaphragm to direct the currents, would in all probability have improved the result.

II. *Heat Transmission.*—In dealing with the conditions under which transmission of heat takes place, M. Hirsch adopted the division of the subject usual since Fourier, and considered (1) the exterior conductivity from hot gases to metal, (2) the interior conductivity of the metal itself, and (3) the exterior conductivity from iron to water. It is in the first division that the greatest losses of heat have taken place almost universally hitherto in boiler practice, although mal-arrangement may, and no doubt often does, give a bad result in the third division also. The interior conduction in a homogeneous metal is nearly constant, and once the permanent state of affairs between the two faces is established, the temperature varies with the distance between them according to an arithmetical progression, and the quantity of heat which traverses the plate is proportional to the difference between the temperatures of two points situated at infinitely small distances from the two faces.

As to exterior conduction, or the property in virtue of which exchanges of heat take place between metal and fluids bathing its surfaces, the laws which govern these exchanges are, as M. Hirsch remarked, not well understood, but it is certain that, all things being equal, the rate of transmission increases when the difference of temperature between the metal and the fluid in contact with it becomes greater.

It is also certain that this transmission is influenced by the condition of the surface of the metal, by the movement of the fluids, etc. The transmission of heat through the metal and also from the metal to the water takes place very readily, so that with a very small difference between the temperature of the iron and that of the water, heat passes in large quantities freely—always provided that there are no thick incrustations or coatings of oily matters. The communication of heat from a liquid is much more active than from a gas, so that the face next the water is

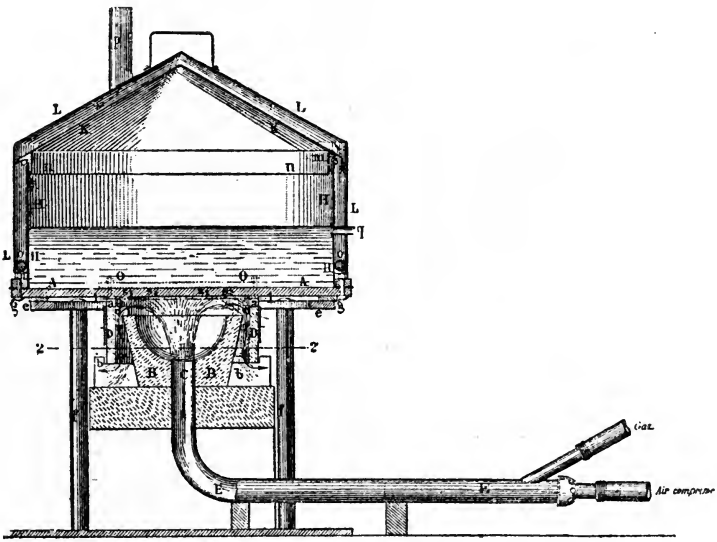

FIG. 73.

never much higher in temperature than the water, whilst the other face is at a much lower temperature than that of the hot gases.

In investigating these matters, M. Hirsch employed the arrangement of apparatus shown in Figs. 73, 74, and 75, consisting of a circular disc of fine boiler plate, A A, 10 millimetres (about $\frac{3}{8}$ in.) thick, and 40 millimetres (or 15·7 ins.) diameter, machined on both surfaces. A cylinder of copper, H H, bolted to the plate at its outside circumference, formed a small boiler or cylindrical dish for the water, and this was surmounted by a conical top, K K, and surrounded by a complete casing, L L, leaving a space, around the cylinder and over the conical cover,

into which the steam was allowed to escape, so that there should be as little priming water carried away as possible. A furnace

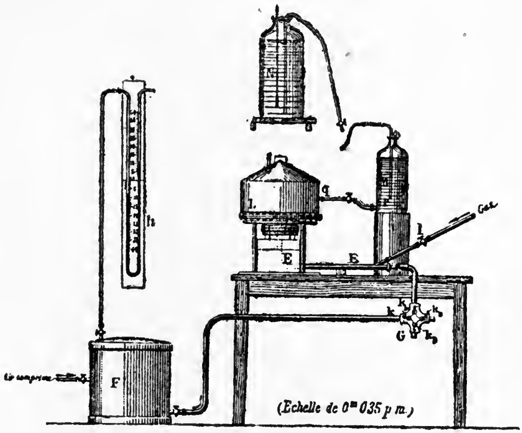

FIG. 74.

was formed of a crucible, B B, of fireclay pierced at C by a pipe E, which conducted the gas and air under pressure to give a

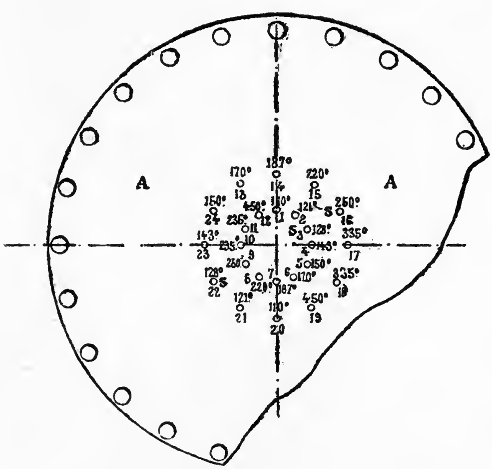

FIG. 75.

blow-pipe flame. A casing, D D, surmounted the crucible, and the flame striking upwards on the plate A, passed over the top

of the crucible and descended inside the casing D and out at *b*. The evaporation of water was reckoned as being that from the area of plate comprised within the cylinder casing D D (16 millimetres diameter ; 6⅜ ins.).

Apparatus for regulating the supply of water and maintaining a constant level was provided, and on the under surface of the plate, in the zone of heating, M. Hirsch introduced a number of fusible plugs of alloys having different melting points. These were disposed in two concentric circles (one 2⅜ in. diameter and the other 4¾ ins. diameter) in such a way that two plugs having the same melting point were placed one in the inner circle and the other at the opposite point in the outer circle. This precaution was taken to guard as much as possible against the effects of local inequalities of heating. Fig. 75 shows the arrangement.

IN THE INNER CIRCLE.

										Lead.		Zinc.
Nos. of the plugs ...	1	2	3	4	5	6	7	8	9	10	11	12
Melting temperatures C.	110°	121°	128°	143°	150°	170°	187°	220°	250°	335°	335°	450°
F.	230°	249·8°	262·4°	289.4°	302°	338°	368·6°	428°	482°	635°	635°	842°

IN THE OUTER CIRCLE.

Nos. of the plugs ...	13	14	15	16	17	18	19	20	21	22	23	24
Melting points C.	170°	187°	220°	250°	335°	335°	450°	110°	121°	128°	143°	150°
F.	338°	368·6°	428°	482°	635°	635°	842°	230°	249·8°	262·4°	289·4°	302°

The range was thus from 230° F. to lead at 635° F., and zinc at 842° F.

M. Hirsch's first experiments were made with distilled water and a clean plate. In an experiment made on August 23rd, 1887, the temperature of the plate, as indicated by the fusible plugs, melted and intact, was between 338° F. and 369° F., and water was evaporated at the rate of 29·59 lbs. per hour per square foot of heating surface. This result was plotted in a diagram, Fig. 76, and was reproduced with a number of those most regularly carried out in another diagram, Fig. 77, in which the abscissæ represent the quantity of water evaporated per unit of surface per hour, and the ordinates the temperatures of the plate. Two lines, A A and B B, are traced on the diagram, showing the variations of temperature of the inner and outer circles of plugs as compared with the amount of water evaporated, and a third line, C C, gives a mean of these variations. M. Hirsch concluded from his various experiments that the temperature of the surface of the plate was never uniform throughout ; it was hotter at the inner

circle of plugs, where the flame had more direct action, than at the outer circle, the difference being about 29° F. The

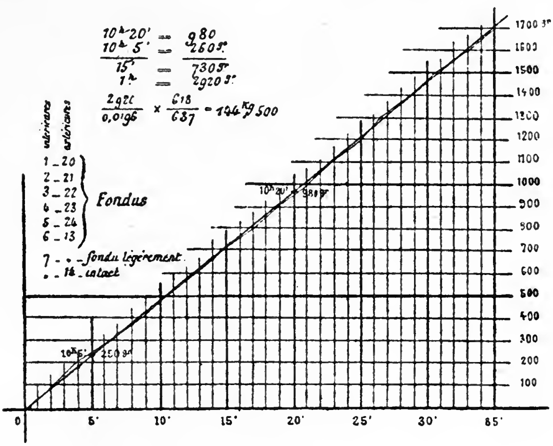

FIG. 76.

temperature of the surface exposed to the fire rises progressively with the increase of the quantity of heat transmitted through the

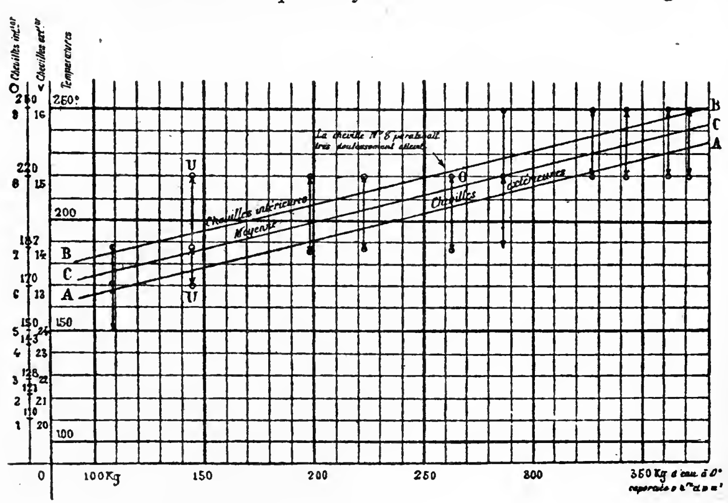

FIG. 77.

plate. To read the phenomena aright, however, we should, according to M. Hirsch consider rather the excess of the

temperature of the plate over that of the water, which was constant at 212° F. He thus found that, with an evaporation of 20 lbs. per square foot per hour, the difference of temperature was 167° F.; it was nearly 212° F. for an evaporation of 40 lbs. per square foot, but it would not reach 302° F. (according to line B B on diagram Fig. 77) until an evaporation was obtained of 75 lbs. per square foot per hour.

If the temperature of the water rises in any boiler, this difference between plate and water does not increase in proportion. Thus, for instance, if we have an iron firebox with plates of $\frac{3}{8}$ in. thickness, supplied with water at a temperature of 356° F. (there being an effective pressure of 8·5 kilogrammes per metre carré = 10 atmospheres or 146 lbs. per square inch), and evaporating 40 lbs. of cold water per hour per square foot, the corresponding difference of temperature should be 212° F., but the temperature of the iron plate never reaches 568° F.

It is well known that if a small boiler be made of paper and held over the flame of a candle, the water will boil but the paper will not be burned. M. Hirsch repeated this experiment in various forms, using the flame of a large Bunsen burner and that of a blow-pipe used in enamelling, which melted glass in a few moments, but the result was always the same. The paper would burn down to the level of the water and a sheet of paper placed over the flame in contact with the bottom of the boiler would instantly be burned up, but the boiler itself when containing water was never attacked by the flame.

These various facts and figures satisfied M. Hirsch that there is no danger of overheating the metal plates of boilers, whatever may be the activity of evaporation, if the metal be sound and in direct contact with the water.

There are, however, other conditions which may intervene to check the transmission of the heat, and these may be found either in the metal itself or interposed between the metal and the water. Consequently, M. Hirsch carried out other experiments in order to study these conditions.

Effects of Increased Viscosity of Water.—The effects of water of increased viscosity were imitated by mixing starch with the water, in proportions successively of 0·2 per cent. and 0·5 per cent. of the weight of water used. With the smaller proportion the temperature difference was raised only about 15° C. (or

59° F.) above that which was registered with distilled water alone. Although the water mixed with 0·5 per cent. of starch was certainly more viscous, the line of temperature appeared not to be elevated to any serious extent.

M. Hirsch points out that this latter proportion of starch is rarely if ever reached, even when amylaceous materials are used to prevent the formation of incrustations, but that even to that limit they do not present any great inconvenience or danger of overheating.

Effects of Incrustations.—The conditions of boilers having incrustations of various thicknesses were then imitated by means of layers of plaster put on the interior surface of the plate. With a layer of plaster $\frac{1}{25}$th inch thick it was necessary to employ a comparatively gentle degree of heat to prevent cracking of the layer, so that the experiment did not go beyond a rate of evaporation of 39 lbs. per hour per square foot of surface. The temperature difference was found to be about 30° C. (or 86° F.) higher than when distilled water was in direct contact with the plate.

With a layer of plaster of $\frac{3}{16}$ths inch thickness, to evaporate 30 lbs. of water caused the external temperature of the plate to rise above 482° F. and to evaporate 40 lbs. it exceeded 752° F., these results being 75° F. and 410° F. respectively above those obtained with water in immediate contact with the plate.

With this thickness of plaster an evaporative rate of 44 lbs. was reached, but the plaster then cracked and separated from the plate.

Effects of Flaws and Joints.—The effects of flaws in the substance of the metal, and of joints, upon the passage of the heat, were ascertained in a very ingenious manner. In a joint or seam, the two parts of the metal are brought together as closely as possible, and it is mainly the additional thickness which is objectionable—the continuity of the metal for heat conduction is but little interfered with. In the case of a flaw, on the other hand, the parts of the metal are kept apart by a small layer of foreign matter. The joint was imitated as follows: Upon the face of the plate touching the water a sheet of steel $\frac{3}{16}$ths inch thick, carefully planed and fitted, was placed, care being taken that both were in contact at all parts of their surfaces. A sheet of tinfoil was laid between them and when the plates were

heated and the tin melted, the two plates were then drawn tightly together by bolts, so that a part of the melted tin was expelled and a perfect soldered joint made.

Evaporative experiments carried out with the plate in that condition showed that the temperature line in the diagram was almost parallel to that obtained with the single boiler plate, except when the rate of evaporation was high. The discrepancy which for an evaporation of 100 kilogrammes per square metre, or 20 lbs. per square foot per hour, was about 50° C. (or 122° F.), reached 70° C. (or 158° F.) for an evaporation of 300 kilogrammes, or 60 lbs. per square foot. At this latter point the temperature of the surface of the plate exposed to the fire was more than 392° F. above that of the water.

Flaws in the metal were imitated by strewing the interior surface of the plate with finely-powdered talc, and then affixing the sheet of steel to the plate by means of bolts screwed up till a distance of only $\frac{1}{250}$th inch separated the two. When the boiler was then filled with distilled water and put in action, with an evaporation of 30lbs. per hour per square foot of heating surface, the temperature of the plate exceeded 662° F., being 270° in excess of that which it had acquired when in direct contact with the water. With an evaporation of 50 lbs. all the plugs, even those of zinc, melted, showing that the temperature of the surface exceeded 842° F., and the plate was in great danger of being overheated. Such would be the effects of flaws in that part of the metal exposed to the fire.

Effects of Contact with Hot Brickwork.—In order to ascertain if the idea were correct that the plates of boilers could be overheated by contact with incandescent brickwork, M. Hirsch filled his furnace with pieces of fire-brick, leaving free passage for the flame between them, so that the plate of his experimental evaporating dish would rest on them when in position for work. The results of this experiment were, an evaporation of 35 lbs. of cold water per hour per square foot of heating surface, the fusible flugs, Nos. 7 and 14 (368·6° F.) having melted, and those of Nos. 8 and 15 (428° F.) remaining intact. These were precisely the results obtained in the first experiments with distilled water under normal conditions of the apparatus, and show that the presence of the firebricks does not influence the transmission of the heat.

In Fig. 78 all the various mean temperature lines are assembled in one diagram for the purpose of comparison. Referring to the first part of his researches, M. Hirsch noted that the evaporation in ordinary cylindrical land boilers, as used for manufacturing purposes, does not exceed, at the part directly exposed to the fire, 20 to 28 lbs. per hour per square

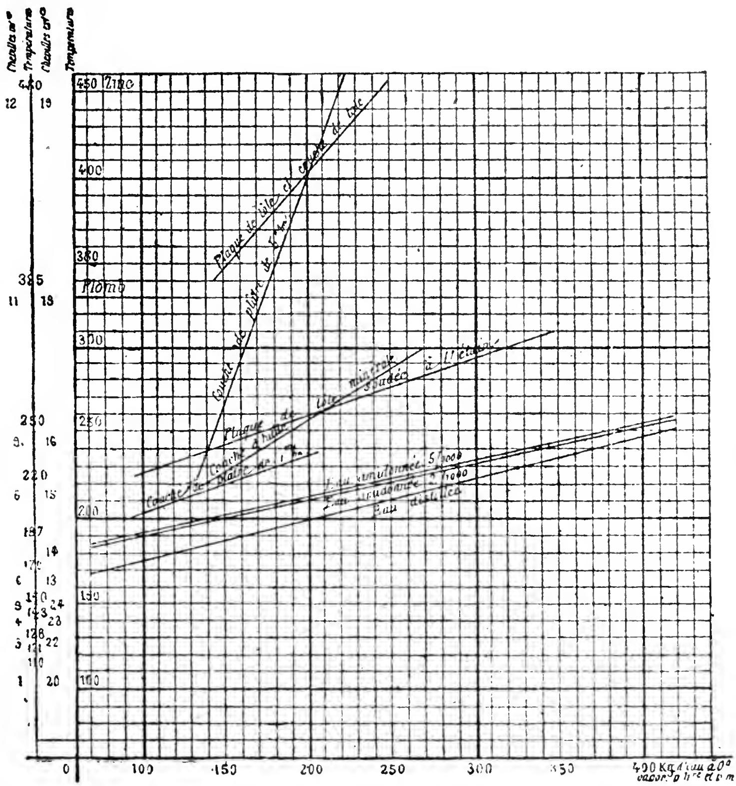

FIG. 78.

foot of heating surface, and that it was improbable that the rate could go with such boilers to 51 lbs. per square foot, even with the strongest fire. The temperature lines in these diagrams showed, however, that dangerous differences of temperature between metal and water need not be expected short of an evaporation of from 80 to 102 lbs. per square foot per hour.

III. *Effects of Oil and Grease.*—In this portion of his experiments, M. Hirsch led the van in inquiring into the effects which the presence of oil and grease upon the surface of iron plates had on the transmission of heat. In the experiments just described, he was decidedly in advance of all previous inquirers in his attempt to measure the actual temperature of the iron of boilers by means of fusible plugs.

In this last division he commenced by covering the interior surface of the plate with mineral oil, which was then wiped off, and left a greasy layer of no appreciable thickness, but sufficient to prevent the adherence of the water to the iron. The boiler was filled up with distilled water, and the experiment conducted as in previous instances. It was found that even when the heating was kept moderate, the exterior surface of the plate reached temperatures notably higher than was the case when the water came into direct contact with the interior surface. With a strong flame peculiar phenomena were observed. In certain cases the increase of temperature coincided with the increased intensity of the fire. The difference between the temperature of the water and that of the exterior surface of the plate was (50° C.), 122° F. higher than in the experiments with pure water, with an evaporation of 30 lbs. per hour per square foot of heating surface. With an evaporation of 50 lbs it was (80° C) 176° F. higher, and the temperature of the flame surface was (200° C.) 392° F. above that of the water. In other cases the results were entirely different ; even after moderate heating, and an evaporation of only 35 lbs., all the fusible plugs were found melted, which was held to prove that the temperature of the plate had been above 842° F. for the major part of its thickness. The effects of oiling the inner surface of a boiler may thus be manifested in two different ways ; either in a moderate increase in the temperature of the heated surface, or with a fire of ordinary intensity the metal becomes heated to a very high degree.

Qualitative Experiments. Effects of Grease.—In order to observe further the effects produced by oily materials, M. Hirsch abandoned his special quantitative apparatus and used some small tinned saucepans, placed on his crucible-shaped furnace, for some qualitative experiments. He had observed that where an abnormal elevation of temperature was attained in the

experiments, black patches, apparently arising from the partial decomposition of fatty matter, adhered to the boiler at the beginning of the trial, not having been completely removed by the cleansing. Wishing to discover if they had any influence on the phenomena of the transmission of heat, he greased a clean tinned saucepan with mineral lubricating oil (*oléonaphte*) and heated it without water over a slow fire to decompose the fatty matter. The bottom of the saucepan was found to be covered with a black coating to which water would not adhere. The saucepan was then filled with water, and heated over the furnace. After boiling a minute one part at the bottom of the saucepan was seen to become red hot, and the incandescence soon spread over the rest of the area covering the opening of the furnace. Evidently the bottom of the saucepan was never wetted, and the water assumed the spheroidal condition. Even if the grease was confined to a limited portion of the bottom, that part alone became incandescent at first, but the red heat gradually extended over all the surface exposed to the fire. This experiment was repeated several times with different intensities of fire. With heat corresponding to an evaporation of about 54 lbs. per hour per square foot of heating surface, the colour of the bottom was bright orange, but when 30 lbs. were evaporated the colour was dark cherry.

Further experiments showed the following results : If a perfectly clean tinned iron saucepan is used, however intense the flame, the water boils in the usual way, and the tin is not melted. The surface is not affected by the heat when the tinning has been removed by scraping or by oxidation, either by the action of humid air or by that of ammonia or hydrochloric acid. In either state of the surface a thin layer of (*oléonaphte*) mineral oil, applied cold, does not interfere with regular ebullition. But if the oil is previously decomposed by heat, or if an oily rag is laid on the bottom of the saucepan and held there by a weight, over-heating immediately takes place. The same effect is produced if a solution of salt is evaporated in an oxidised saucepan, and the bottom, when covered with a thin crust of salt, is smeared with cold mineral oil. The smallest quantity of linseed oil at the bottom of the saucepan immediately produced over-heating even with the low rate of evaporation of 20 to 24 lbs. Spirits of turpentine and oil of turpentine did not produce

overheating, unless mixed with a small quantity of linseed oil. A mastic of red lead easily produced overheating, but not so quickly with colza oil as with linseed oil. Valvoline, when laid on cold, only caused a dangerous glow when the heat was very intense—equivalent to a 70-lbs. evaporation.

Pitch at the bottom of the tinned saucepan floated off when the water boiled ; it adhered to an oxidised surface, but did not cause the iron to become unduly heated.

Limiting Circumstances to the Value of Experiments.—These investigations are undoubtedly unique, both in design and in importance as regards our subject, and they were the forerunners of similar inquiries by Durston, Blechynden, and Bryant. There are, however, some circumstances which limit their value as applied to the larger question of boiler operation.

1. A flat, horizontal surface, such as that of the plate experimented with, is the worst for freedom of supply of water by circulation when boiling, and consequently this must limit the amount of heat which can be transmitted through it. This acts in two ways. The total evaporation in a given time per unit of surface is lessened, and the degree of heating the plate is increased. A dish-shaped plate, formed like the contour of the section of the furnace, would have been better for the water circulation ; but even in that case the movement of the water could not have been as rapid as the escape of the steam formed, in consequence of the difference in density and viscosity of the two fluids.

2. The plate used in M. Hirsch's experiments extended a considerable distance beyond the furnace, and consequently some heat was conducted to the outer portion and dissipated by contact with the air. From these causes it is probable that the plate in the region of the furnace attained a higher temperature than should be necessary for a given evaporative rate, and yet that all the heat employed was not usefully applied.

3. The use of fusible plugs as indicators of temperatures, however, renders it uncertain whether the temperatures recorded were actually reached by the plate. Apart from the cause of uncertainty referred to in Chapter II., p. 35, the junction of metals of diverse conductivities, both thermal and electrical, introduces another doubtful element, and it seems certain, from the later researches of Miss E. M. Bryant, that the

actual temperature of the plate is always less than the one indicated by the melting plugs.

Nevertheless, the experiments give proof that an evaporation of from 50 to nearly 100 lbs. of water per hour per square foot of heating surface, may be attained, without serious heating of the metal of boilers, when these are properly constructed and the surfaces are clean.

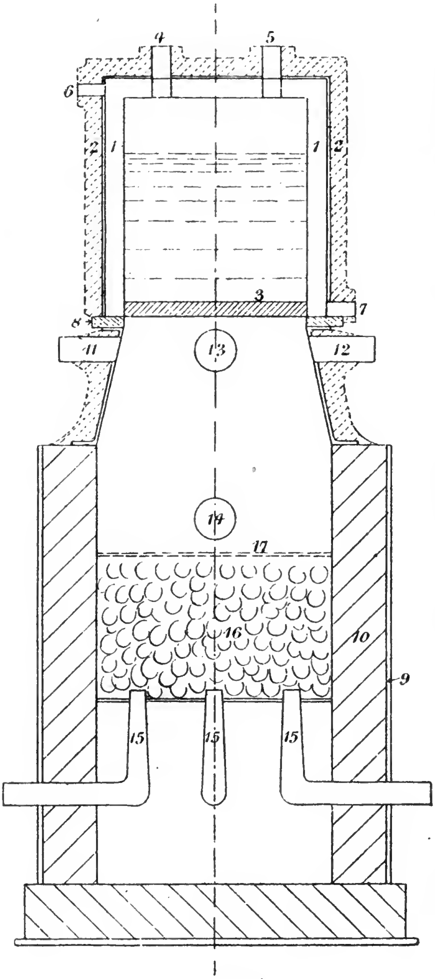

FIG. 79

Blechynden's Experiments.—The experiments carried out by Mr. Blechynden, in 1893, are even more unsatisfactory, from the point of view of the circulation of the water and gases, than those of M. Hirsch, although Mr. Blechynden took precautions against loss of heat by radiation, which, as we have seen, M. Hirsch to a large extent neglected. The diameter of Mr. Blechynden's dish, or "boiler," was smaller than that of M. Hirsch's, and the furnace was not so well arranged, but the full diameter of the plate was embraced by the furnace casing.

Mr. Blechynden's apparatus is illustrated in Figs. 79 and 80, in which A is the boiler, B the furnace, C and D are openings for measuring temperatures, and E and F openings for escape of

the hot gases. The boiler (A) was 10 inches in diameter and 12 inches high outside, and was constructed of tinned iron plate about 24 B.W.G. in thickness, with a jacket 1 inch wide (1) on its sides and top, covered with (2) asbestos felt ·375 inch thick. Usually air was employed in the jacket, but steam could be admitted by the inlet (6) and made to pass through to the outlet (7). At first the boiler was covered with only asbestos felt, without the air space or jacket. The plate to be experimented with (3) formed the bottom of the boiler, which was soldered to it, the two pipes (4) and (5) at the top providing for the admission of water, the escape of steam, and the insertion of mercury thermometers to register the temperature of the water. The furnace was a cylindrical chamber (9) of sheet iron, lined with firebrick (10), (11) and (12) being the openings near the top for exit of the gases, and (13) and (14) holes for insertion of the copper balls or blocks forming part of a Siemens' pyrometer, which was used for measuring the furnace temperatures. Five jets (15) of ordinary lighting gas, with an air blast from a smith's fire supplied flame, which was passed through a mass of asbestos lumps (16), covered with a layer of wire gauze (17) in order to distribute the flame evenly. At (13) the

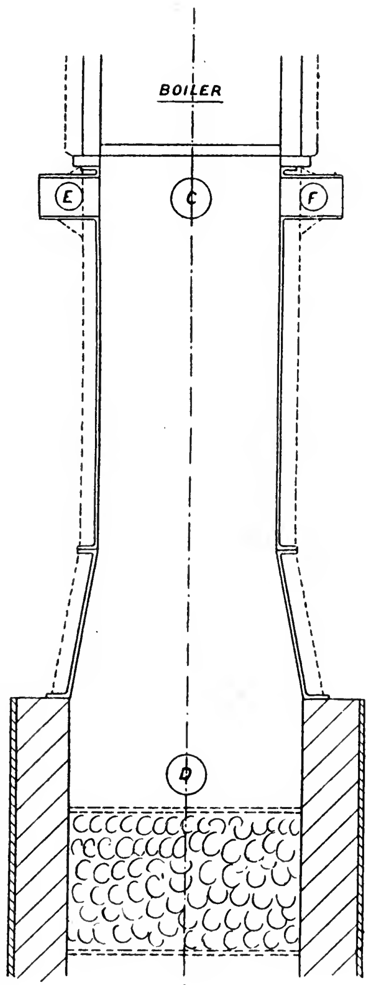

FIG. 80.

pyrometer block was suspended at a distance of one quarter to one half inch from the surface of the plate, and at (14) the block was about two inches from the incandescent mass of asbestos.

Mr. Blechynden admitted to some extent the uncertainty of the record of temperatures afforded by the Siemens' pyrometer, but his estimate of error was too low. Such a method can afford merely a rough approximation to the actual temperature of the spot where the copper block is heated.[1] The arrangement of exit tubes or passages (11) and (12) for the escape of the hot gases was, moreover, such that there could be no proper current of these hot gases in contact with the heating surface, that surface itself being also of a bad form and in a bad position for a good result. If the top of these exit tubes had been level with the bottom surface of the plate (3), this would have ensured a constant renewal of the portions of gas in contact with the plate surface, and would have prevented the formation of local eddies, which Mr. Blechynden's arrangement favoured. It follows from this that even the temperatures registered by the apparatus at C were not likely to have been the temperatures at the underside of the plate. Further, as to the possibility of adequate circulation of the water, it is evident that Mr. Blechynden relied entirely upon the natural movement produced by the act of boiling in the confined space of the vessel, but, of course, that movement depended on the rate at which ebullition proceeded in this special vessel, and was, further, hindered by the limited quantity of water, which was all above the portion of the vessel being heated. Under the circumstances, there could not have been realised as good a result as would have been reached with additional movement of the water and gases over the surfaces of the plate. Apart from these defects, which were inherent to the process employed, the experiments were most carefully carried out and considered. First of all, the temperatures were tested by removing the boiler and covering the opening with asbestos sheet and an iron plate. Under such conditions the temperature reading obtained at C, D, E, and F was the same, viz., 1780° F. The boiler was then

[1] See "Trans. Inst. Eng. and Shipbuilders in Scotland," Vol. xxxv., pp. 143, 144.

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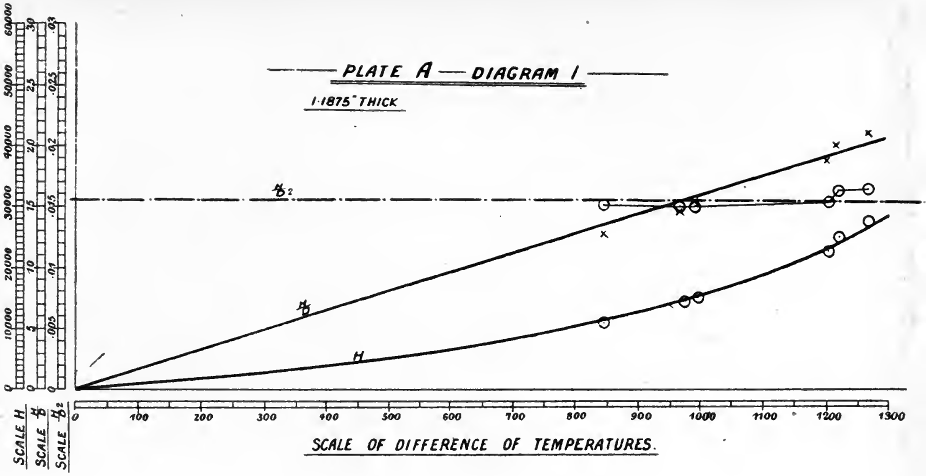
PLATE A — DIAGRAM I
1·1875" THICK
H/D²
H/D
H
SCALE H
SCALE H/D
SCALE H/D²
SCALE OF DIFFERENCE OF TEMPERATURES.

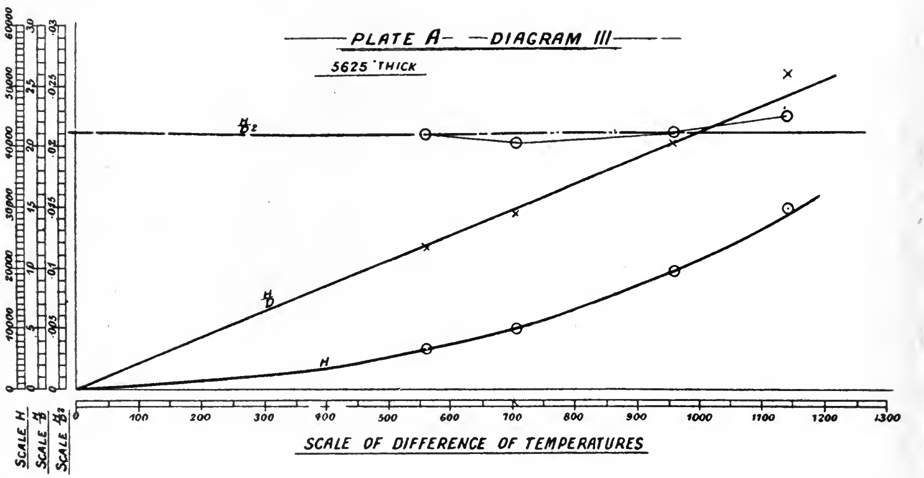
PLATE A — DIAGRAM III
·5625" THICK
H/D²
H/D
H
SCALE H
SCALE H/D
SCALE H/D²
SCALE OF DIFFERENCE OF TEMPERATURES

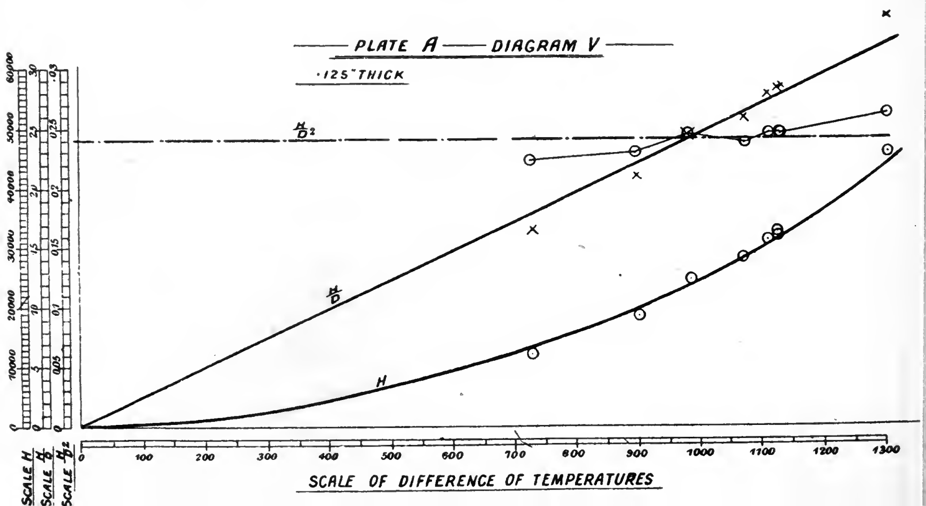
PLATE A — DIAGRAM V
·125" THICK
H/D²
H/D
H
SCALE H
SCALE H/D
SCALE H/D²
SCALE OF DIFFERENCE OF TEMPERATURES

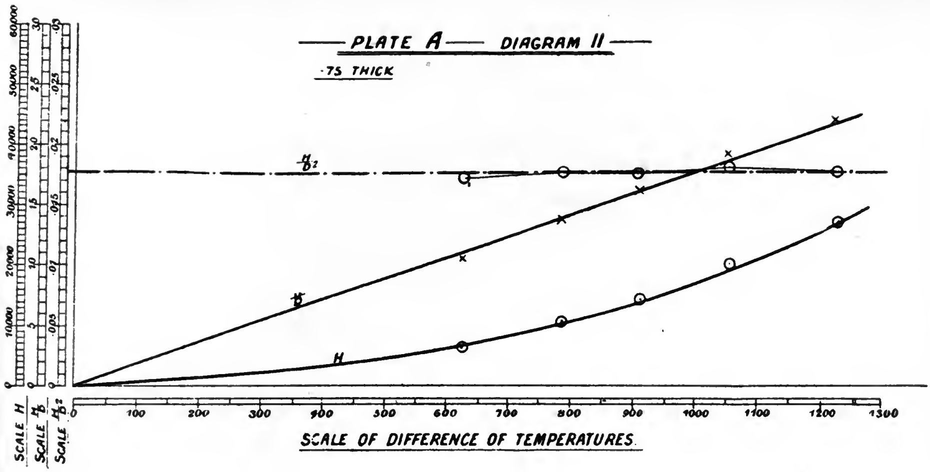
PLATE A — DIAGRAM II
·75 THICK
SCALE H
SCALE H/D
SCALE H/D2
SCALE OF DIFFERENCE OF TEMPERATURES.

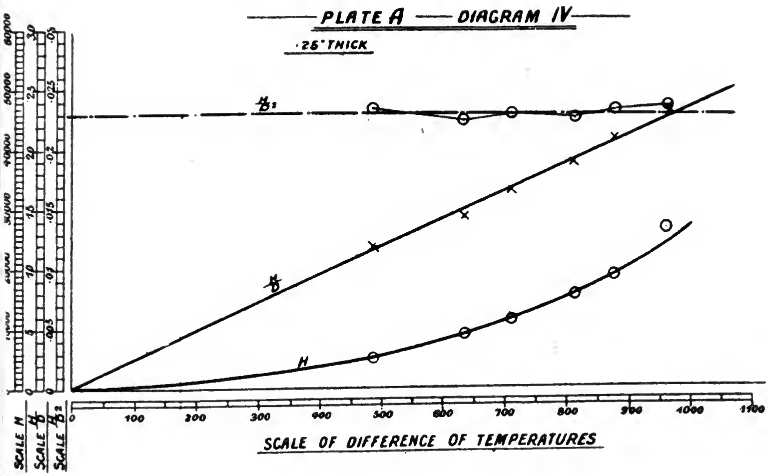
PLATE A — DIAGRAM IV
·25" THICK
SCALE H
SCALE H/D
SCALE H/D2
SCALE OF DIFFERENCE OF TEMPERATURES

replaced, and the temperature readings were obtained as follows :—

At E, F, and C	1545° F.
At D	1850° F.
At a point $3\frac{1}{2}$ ins. under the plate	1580° F.

Mr. Blechynden very properly remarks on these facts : "It will be evident, from the latter experiment, that a comparison of the evaporative results, or the quantity of heat transmitted with the temperatures measured at C, would be misleading, and would incorrectly represent the modulus of transmission, unless the quantity of heated gas passing over the surface of the plate were unlimited ; the comparison should be with some function of the initial and terminal temperatures. But, as in a considerable number of the earlier experiments the temperatures at C only were measured, a comparison of the evaporative results will be made with these temperatures, from which it will be seen that such broad general results will be obtained that, with a simple correction for the fact of the temperatures being terminal, the true coefficient of transmission may be fairly approximated." It is thus apparent that Mr. Blechynden had no idea of attaching to these experiments anything like the final or absolute value which many have invested them with since their publication, and therefore that any relation found to exist between the temperatures observed and the quantity of heat transmitted, does not necessarily hold good for any other conditions than those under which these observations were made, or for any other form or arrangement of apparatus.

The results of the experiments are given in the following Tables, XXXII. to XXXIX., and are also shown graphically in the diagrams, Figs. 81 and 82, giving the general results for all the plates shown relatively to each other :—

TABLE XXXII.

RESULTS OF EXPERIMENTS ON THE TRANSMISSION OF HEAT THROUGH STEEL PLATES.

No. 1. PLATE A. (SIDE NEXT WATER MACHINED).

Duration of Trial.	Temperature in Furnace at C.	Total Lbs. of Water Evaporated.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units lost by Radiation per Hour.	Total Units (with Radiation) Transmitted per Hour per Sq. Ft. H.	Difference in Temperature D.	Heat Units Transmitted per 1 deg. Diff. per Sq. Ft. per Hour $\frac{H}{D}$.	$\frac{H}{D}$.	Thickness of Plate.
Hrs. Mins.	Deg.								
1 51	1,060	10·15	5,300	600	10,820	848	12·78	·01505	1·1875
1 49	1,205	14·0	7,460	"	14,780	993	14·85	·01498	"
1 27	1,225	8·11	7,845	"	15,500	1,013	15·26	·01505	"
2 3	1,425	25·1	11,800	"	22,750	1,213	18·73	·01545	"
1 54	1,440	25·1	12,750	"	24,450	1,228	19·9	·01622	"
2 37	1,490	38·05	13,950	"	26,750	1,278	20·9	·01637	"
							Mean	·01552	

No. 2. PLATE A.

1 4	838	3·44	3,120	600	6,820	626	10·89	·01741	·75
2 1	1,000	11·27	5,380	"	10,950	788	13·9	·01765	"
2 1½	1,125	15·45	7,380	"	14,650	913	16·04	·01757	"
1 33	1,270	16·79	10,480	"	20,300	1,058	19·18	·01811	"
1 48	1,445	26·45	14,150	"	27,100	1,233	21·92	·01788	"
							Mean	·01770	

No. 3. PLATE A.

2 6	775	6·65	3,058	600	6,705	563	11·90	·02110	·5625
1 57	920	9·97	4,950	"	10,180	708	14·37	·02030	"
1 8½	1,175	11·85	10,000	"	19,450	963	20·18	·02094	"
1 7	1,360	17·98	15,500	"	29,550	1,148	25·7	·02241	"
							Mean	·02119	

TABLE XXXIII.

No. 4. PLATE A. (SIDE NEXT WATER MACHINED).

Duration of Trial.	Temperature in Furnace at C.	Total Lbs. of Water Evaporated.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units Lost by Radiation per Hour.	Total Units (with Radiation) Transmitted per Hour per Sq. Ft. H.	Difference in Temperature D.	Heat Units Transmitted per 1 deg. Diff. per. Sq. Ft. per Hour $\frac{H}{D}$.	$\frac{H.}{D^2}$.	Thickness of Plate.
Hr. Mins.	Deg.								
1 51	715	5·06	2,645	600	5,950	503	11·81	·02350	·25
1 25	858	6·52	4,450	"	9,260	646	14·35	0·2230	"
1 19	935	8·11	5,930	"	11,970	723	16·55	0·2290	"
1 14	1,040	9·97	7,820	"	15,450	828	18·65	0·2255	"
1 7	1,105	10·9	9,460	"	18,470	893	20·65	0·2310	"
1 7	1,190	13·61	11,750	"	22,650	97	23·15	0·2365	"
							Mean	·02300	

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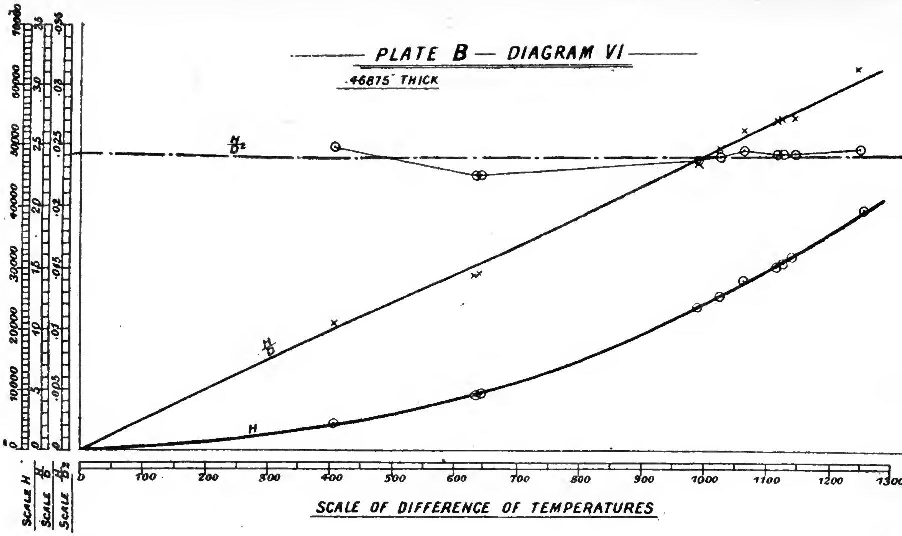


PLATE B — DIAGRAM VI
.46875" THICK
$\frac{H}{D^2}$
$\frac{H}{D}$
H
SCALE H
SCALE $\frac{H}{D}$
SCALE $\frac{H}{D^2}$
SCALE OF DIFFERENCE OF TEMPERATURES

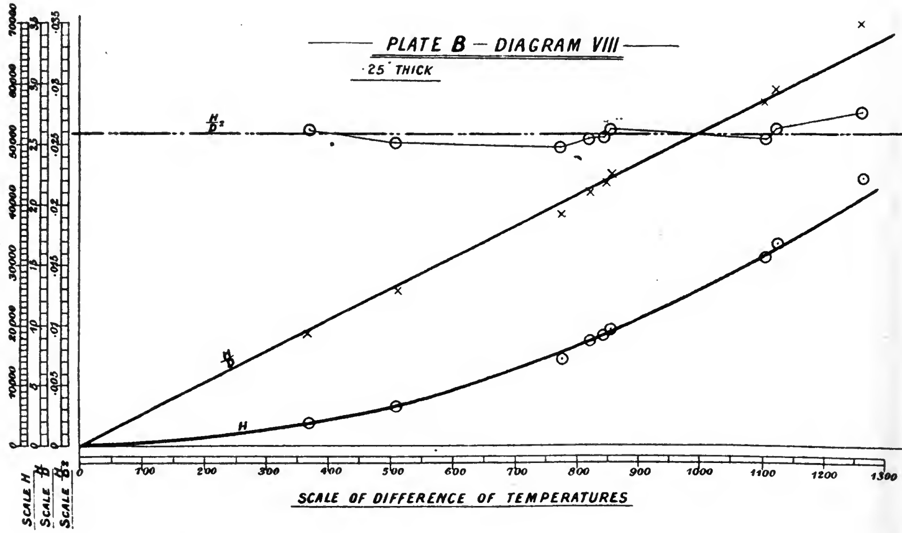
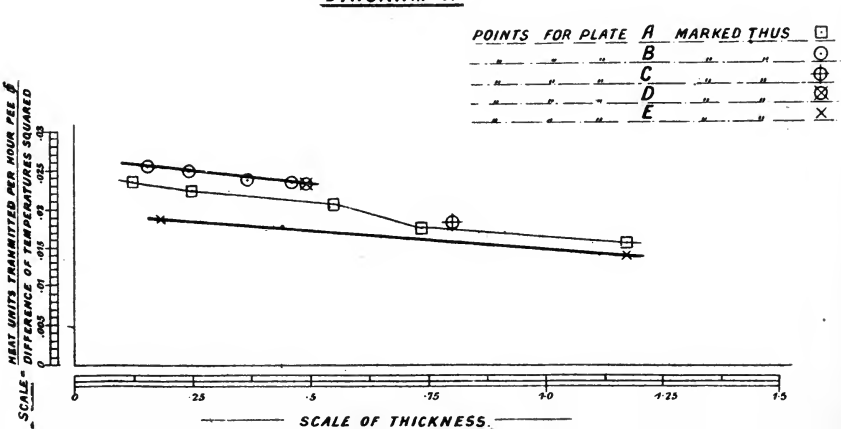


PLATE B — DIAGRAM VIII
·25" THICK
$\frac{H}{D^2}$
$\frac{H}{D}$
H
SCALE H
SCALE $\frac{H}{D}$
SCALE $\frac{H}{D^2}$
SCALE OF DIFFERENCE OF TEMPERATURES

— DIAGRAM X —


POINTS FOR PLATE A MARKED THUS
" " " B " "
" " " C " "
" " " D " "
" " " E " "
SCALE = HEAT UNITS TRANSMITTED PER HOUR PER ☐ / DIFFERENCE OF TEMPERATURES SQUARED
SCALE OF THICKNESS.

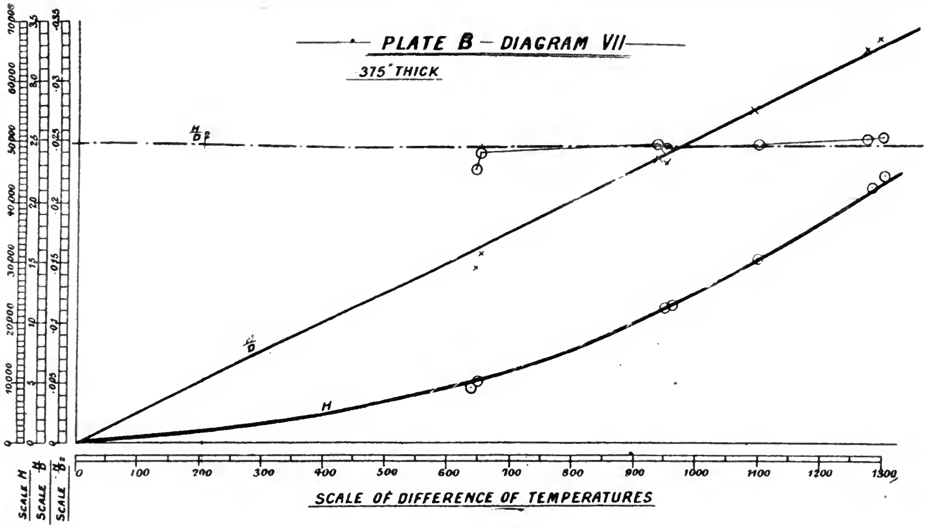


PLATE B — DIAGRAM VII
·375" THICK
H/D²
H/D
H
SCALE H
SCALE H/D
SCALE H/D²
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
SCALE OF DIFFERENCE OF TEMPERATURES

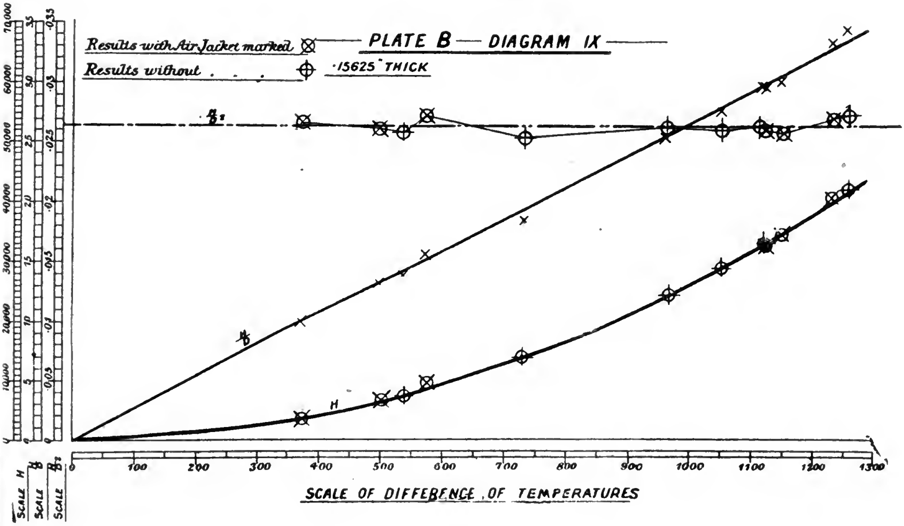

Results with Air Jacket marked ⊗
Results without . . . ⊕
PLATE B — DIAGRAM IX
·15625" THICK
H/D²
H/D
H
SCALE H
SCALE H/D
SCALE H/D²
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
SCALE OF DIFFERENCE OF TEMPERATURES

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TABLE XXXIII. (*continued*).

No. 5. PLATE A.

Duration of Trial.	Temperature in Furnace at C.	Total Lbs. of Water Evaporated.	Heats Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units lost by Radiation per Hour.	Total Units (with Radiation) Transmitted per Hour per Sq. Ft. H.	Difference in Temperature D.	Heat Units Transmitted per 1 deg. Diff. per Sq. Ft. per Hour. $\frac{H}{D}$.	$\frac{H}{D_2}$.	Thickness of Plate
Hr. Mins.									
1 3	950	6·55	6,030	600	12,170	738	16·48	·02230	·125
1 1	1,120	10·18	9,690	„	18,850	908	20·75	·02285	„
1 25	1,210	18·27	12,500	„	24,030	998	24·1	·02415	„
1 6	1,295	16·48	14,460	„	27,620	1,083	25·48	·02352	„
1 24	1,335	23·28	16,100	„	30,620	1,123	27·25	·02426	„
1 13	1,345	20·45	16,240	„	30,900	1,133	27·27	·02410	„
1 13	1,350	20·65	16,450	„	31,300	1,138	27·48	·02410	„
1 3	1,530	26·10	24,000	„	45,100	1,318	34·21	·02595	„
							Mean	·02390	

TABLE XXXIV

No. 6. PLATE B. (SIDE NEXT WATER MACHINED).

Duration of Trial.	Temperature in Furnace at C.	Total Lbs. of Water Evaporated.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units lost by Radiation per Hour.	Total Units (with Radiation) Transmitted per Hour per Sq. Ft. H.	Difference in Temperature D.	Heat Units Transmitted per 1 deg. Diff. per Sq. Ft. per Hour. $\frac{H}{D}$.	$\frac{H}{D^2}$.	Thickness of Plate.
Hr. Mins.	Deg.								
1 10	625	2·09	1,730	600	4,270	413	10·32	·02495	·46875
1 7	850	5·09	4,400	„	9,175	638	14·38	·02255	„
1 23	855	6·41	4,500	„	9,350	643	14·53	·02260	„
1 0	1.205	12·68	12,235	„	23,550	993	23·70	·02385	„
1 30	1,240	20·64	13,300	„	25,500	1,028	24·80	·02410	„
1 8	1,280	17·23	14,720	„	28,140	1,068	26·30	·02462	„
1 19	1,335	21·86	16,000	„	30,450	1,123	27·10	·02410	„
1 0	1,340	16·82	16,230	„	30,850	1,128	27·34	·02425	„
1 3	1,360	18 28	16,800	„	31,940	1,148	27·80	·02420	„
1 0	1,465	21·38	20,610	„	38,950	1,253	31·10	·02474	„
							Mean	·023996	

No. 7. PLATE B.

1 3	862	5·0	4,610	600	9,570	650	14·74	·02270	·375
1 10	868	6·15	5,080	„	10,420	656	15·87	·02421	„
1 17	1,170	15·69	11,800	„	22,750	958	23·74	·02479	„
1 8	1,180	13·92	11,880	„	22,880	968	23·62	·02440	„
1 4	1,320	17·62	16,000	„	30,400	1,108	27·40	·02472	„
1 21	1,500	30·7	22,000	„	41,450	1,288	32·15	·02498	„
1 8½	1,520	27·0	22,910	„	43,150	1,308	33·0	·02520	„
							Mean	·02443	

TABLE XXXV.

No. 8. PLATE B. (SIDE NEXT WATER MACHINED).

Duration of Trial.	Temperature in Furnace at C.	Total Lbs. of Water Evaporated.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units lost by Radiation per Hour.	Total Units (with Radiation) Transmitted per Hour per Sq. Ft. H.	Difference in Temperature D.	Heat Units Transmitted per 1 deg Diff. per Sq. Ft. per Hour. $\frac{H.}{D.}$	$\frac{H.}{D^2.}$	Thickness of Plate.
Hrs. Mins.	Deg.								
1 4	585	1·5	1,360	600	3,595	373	9·63	·02584	·25
1 1	725	3·13	2,975	,,	6,560	513	12·77	·02495	,,
1 10	985	8·93	7,410	,,	14,700	773	19·0	·02460	,,
1 9	1,035	10·45	8,780	,,	17,220	823	20·94	·02544	,,
0 57	1,060	9·25	9,370	,,	18,310	848	21·6	·02545	,,
1 15	1,067	12·66	9,770	,,	19,020	855	22·28	·02600	,,
1 4	1,320	18·15	16,500	,,	31,380	1,108	28·3	·02550	,,
1 12	1,340	21·62	17,460	,,	33,150	1,128	29·39	·02604	,,
1 6	1,480	26·55	23,300	,,	43,800	1,268	34·6	·02730	,,
							Mean	·02568	
				No. 9. PLATE B.					
1 17	755	4·67	3,520	600	7,550	543	13·88	·02558	·15625
1 20	950	9·38	6,780	,,	13,540	738	18·35	·02490	,,
1 3	1,185	14·0	12,850	,,	24,650	973	25·3	·02600	,,
1 7	1,270	17·45	15,150	,,	28,900	1,058	27·3	·02583	,,
1 6	1,335	19·65	17,320	,,	32,900	1,123	29·28	·02604	,,
1 10	1,460	27·8	23,050	,	43,400	1,248	34·8	·02790	,,
1 5	1,475	25·3	22,550	,,	42,400	1,263	33·58	·02658	
				WITH AIR JACKET. NO ADDITION FOR RADIATION.					
	At C & D.								
3 21	588	6·99	2,019	0	3,700	376	9·86	·02625	air jacket
1 36	717	5·96	3,595	0	6,600	505	13·06	·02590	,,
2 0	794	10·28	4,979	0	9,140	582	15·67	·02690	,,
1 46	1,341	32·6	17,850	0	32,750	1,129	29·10	·02570	,,
1 21	1,367	25·95	18,540	0	34,050	1,155	29·48	·02550	,,
1 32	1,450	35·1	22,100	0	40,550	1,238	32·78	·02650	,,
							Mean	·02611	

TABLE XXXVI.

No. 9A. PLATE B. (SIDE NEXT WATER MACHINED). WITH AIR JACKET. NO ADDITION FOR RADIATION.

Duration of Trial.		Temp. at Top of Furnace.	Temp. at Bottom of Furnace.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units Transmitted per Hour per Sq. Ft. H.	D Diff. Top.	d Diff. Bott.	$\frac{H}{D}$.	$\frac{H}{D \times d}$.	$\frac{H}{D^2}$.	Thickness of Plate.
Hrs.	Mins.	Deg.									
1	36	717	867	3,595	6,600	505	655	13·06	·01995	·0259	·0156
2	0	794	904	4,979	9,140	582	692	15·67	·02265	·0269	„
1	46	1,341	1,537	17,850	32,750	1,129	1,325	29·10	·02195	·0257	„
1	21	1,367	1,850	18,540	34,050	1,155	1,638	29·48	·01800	·0255	„
								Mean	·02064		

TABLE XXXVII.

No. 10. PLATE C. (BOTH SIDES ROUGH).

Duration of Trial.		Temperature in Furnace.	Total Lbs. of Water Evaporated.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units lost by Radiation per Hour.	Total Units (with Radiation) Transmitted per Hour per Sq. Ft. H.	Difference in Temperature D.	Heat Units Transmitted per 1 deg. Diff. per Sq. Ft. per Hour $\frac{H}{D}$.	$\frac{H}{D_2}$.	Thickness of Plate.
Hrs.	Mins.	Deg.								
1	3	864	3·95	3,638	600	7,776	652	11·91	·01829	·8125
1	2	975	5·70	5,325	„	10,860	763	14·25	·01865	„
1	1	985	5·93	5,630	„	11,420	773	14·80	·01912	„
1	9	990	6·07	5,100	„	10,450	778	13·46	·01730	„
1	4	990	6·05	5,475	„	11,140	778	14·31	·01841	„
1	5	1,060	6·95	6,200	„	12,475	848	14·70	·01735	„
								Mean	·01819	

TABLE XXXVIII.

No. 11. PLATE D. (SIDE NEXT WATER MACHINED).

Duration of Trial.		Temp. at Top of Furnace at C.	Temp. at Bottom of Furnace at D.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units Transmitted per Hour per Sq. Ft. H.	D Diff. Top.	d Diff. Bott.	$\frac{H}{D}$.	$\frac{H}{D \times d}$.	$\frac{H}{D2}$.	Thickness of Plate.
Hrs.	Mins.	Deg.	Deg.								
1	30	651	743	2,318	4,250	439	531	9·66	·01820	·02200	·5
1	30	967	1,279	7,180	13,200	755	1,067	17·49	·01640	·02316	„
1	31	950	1,354	7,140	13,110	738	1,142	17·75	·01560	·02428	„
1	29	956	1,177	7,400	13,580	744	965	18·23	·01892	·02455	„
2	40	980	1,280	7,620	13,980	768	1,068	18·26	·01710	·02380	„
1	41	1,059	1,396	8,820	16,200	847	1,184	19·13	·01615	·02260	„
1	40	1,091	1,347	10,200	18,730	879	1,135	21·32	·01880	0·2430	„
1	33	1,122	1,422	11,120	20,410	910	1,210	22·45	·01858	0·0247	„
								Mean	·01747	·02367	

TABLE XXXIX.

NO. 12. PLATE E. (MACHINED ON BOTH SIDES).

Duration of Trial.	Temp. Top at C.	Temp. Bott. at D.	Heat Units Transmitted per Hour by Heating and Evaporation of Water.	Heat Units Transmitted per Hour per Sq. Ft. H.	D Diff. Top	d Diff. Bott.	$\frac{H}{D \times d}$.	$\frac{H}{D^2}$.	Thickness of Plate.
Hrs. Mins.	Deg.	Deg.							
I 38	513	735	774	1,420	301	523	·00901	·01560	1·1875
I 53	652	896	1,520	2,790	440	684	·00927	·01442	"
2 0	856	1,125	2,855	5,230	644	913	·00890	·01264	"
2 2	1,285	1,550	8,800	16,150	1,073	1,338	·01126	·01405	"
						Mean	·00961	·01418	

NO. 13. PLATE E. (MACHINED ON BOTH SIDES).

I 32¼	534	648	1,091	2,005	322	436	·01430	·01938	·1875
2 0	771	989	3,276	6,010	559	777	·01382	·01920	"
2 0	955	1,242	5,641	10,360	743	1,030	·01354	·01880	"
I 45	1,340	1,625	13,550	24,880	1,128	1,413	·01559	·01955	"
						Mean	·01431	·01923	

Boiler surrounded top and sides by air jacket, which was well covered with asbestos.
No allowance has been made for loss by *radiation.*
This plate was *machined* on *both* sides.

In discussing his results Mr. Blechynden said, that "if an examination be made of the Diagrams or Tables, the broad general fact is evident that the heat transmitted through any of the plates per degree difference between the fire and the water is proportional to the square of the difference between the temperatures at the two sides of the plate, as will be seen from the fact that the ratio

$$\frac{\text{Heat transmitted per square foot.}}{(\text{Difference of Temperatures})^2}$$

is a constant for each plate within the limits of the experiments, and the mean values of this ratio for the various plates are given in the table.

"The figures for the moduli in the last column are calculated as for the mean of the squares of the differences of the temperatures on the assumption that the temperatures taken just over the fire, or point D, are the maxima, which would be approximately true, and that those at the upper station were equal to those of the escaping gases, which was actually correct. The mean of the squares of the differences of temperatures was taken

Table XL.

Plates.	Thickness. Inches.	Modulus for Temperature at Top Station.	Modulus for Temperature at both Upper and Lower Stations.
A	1·1875	0·01552	
A	·750	·01770	
A	·5625	·02119	
A	·25	·0230	
A	·125	·02390	
B	·46875	·023996	
B	·3750	·02443	
B	·250	·02568	
B	·15625	·02611	·02064
C	· 8125	·01819	
D	·5000	·02367	·01747
E	1·1875	·014178	·00961
E	·1875	·019235	·01431

as being D d, where D is the difference between the temperature at the upper station and the boiler, and d the difference between that at the lower station and that in the boiler.

"The Table shows that there is a general rise in the value of the moduli with decrease of thickness ; but if the diagram Fig.

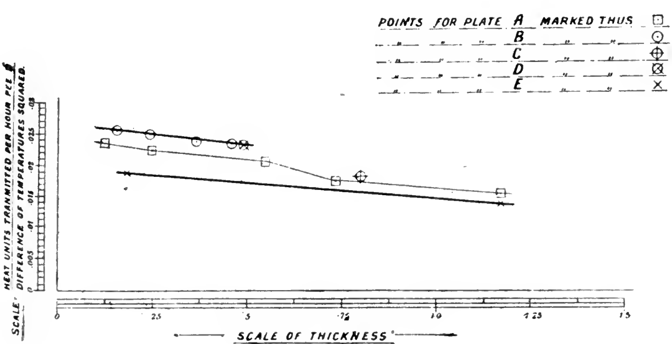


FIG. 82A.

82A, which shows graphically the general relation of these moduli, be inspected, it will be seen that there are considerable irregularities in the curves joining the various points for each plate. This is perhaps no more than might be expected, because of the great difficulty of machining all the surfaces to the same degree of smoothness, and notwithstanding the precautions taken, the difficulty of maintaining the surfaces uniformly

clean. It was found that the very slightest trace of grease caused a very large fall in the rate of transmission; even wiping the outer surface of the plate with a piece of rag or of waste was sufficient to influence the result detrimentally.

"There is also an apparent falling off in the increased efficiency of thinner plates when they are under three-eighths of an inch or so, which seemed as if it might possibly be accounted for on the assumption that the thinner plates yielded to the cutting tool, and thus came to have more smoothly machined surfaces than the thicker. That the smoothness of the plates was an important factor will be readily seen when the position of the points for plate E are compared with the others."

"The results of these experiments," Mr. Blechynden finally remarked, "certainly point to the conclusion that the thinner the plates forming part of the heating surface of a boiler, the higher should be the boiler's efficiency, always provided that the plates are clean; but it will be evident that if the plates be coated with a covering of scale, or some bad conductor, then the less must be the influence of the thickness on the efficiency, while with a thick coat of oil the influence might become practically unimportant. The fact that the heat transmitted is proportional to the square of the difference of the temperatures of the two sides of the plate, shows the importance of high furnace temperatures if efficiency is aimed at, and emphasises the importance of rapid combustion either by means of air supplied by fans or by height of funnel."

We may accept these conclusions without endorsing all the statements connected with them. It is, for instance, evident that the temperatures of the hot gases and of the water—what may be termed the temperatures *at* the two sides of the plate—are confounded with the temperatures *of* the two surfaces of the plate itself. In consequence of the very minute degree of resistance in iron plates to the conduction of heat through the substance of the metal, it is not likely that there can be any considerable difference of temperature between the two surfaces, even while a large amount of heat may be passing per unit of time per unit of surface. For the transmission of a large amount of heat, there must no doubt be a large difference between the temperature of the hot gases and that of the water. The two sets of differences are therefore far from being identical. The

conditions which interpose resistances to the flow or passage of heat from the gases to the water have still to be investigated.

Reichsanstalt Experiments.—Similar experiments to those of Mr. Blechynden were carried out at the Reichsanstalt, Charlottenburg, by Dr. Wiebe and Mr. R. Schwirhus, between 1895 and 1896, and are recorded in the Report of Professor Kohlrausch, the President of the Institution. A comprehensive authorised abstract of the report appeared in the July and August (1896) numbers of the *Zeitschrift für Instrumentenkunde ;* the experiments on tranmission of heat through metallic plates, being at pages 235 to 240, and a short account in English of these experiments was given in *Engineering*, Vol. lxiii., p. 31 (1st January, 1897).

Eleven plates were used in these experiments, of which six were steel, three were wrought iron, and two were copper. All were 25 centimetres (9·84 ins.) in diameter and the original thickness, of either 1·2 in. or 0·75 in., was gradually reduced down to 0·2 in. in some instances. The furnace and boiler arrangements resembled those of Blechynden, except that disc grates were inserted to effect a thorough mixing of the gases and a uniform temperature over the surface of the fire, and Le Chatelier thermo-couples were employed to measure the temperature at 4 centimetres or 1·6 in. below the plate under test.

Seventy-eight experiments were made with the steel plates, 35 with the wrought iron, and 12 with the copper plates.

Originally, both surfaces of the plate were in the state left by the mill or foundry, and the reduction of thickness was effected by turning down the inner surface which was exposed to the water, the outer surface, exposed to the gases, remaining rough. Some tests with plates polished on both surfaces were also made, and one or two with artificial incrustations on the water surface. These imitation incrustations were composed of cement and sand, or of actual boiler crust powdered and mixed with oil, and their thickness was varied between 0·2 and 0·3 in.

The temperature at the fire side of the plate was varied, the quantity of water evaporated at each temperature being observed for a period which extended to from 1 to $2\frac{1}{2}$ hours in different experiments.

All the observations were recorded in a series of diagrams, in which the abscissæ are degrees Centigrade and the ordinates are

kilogramme-calories per hour per degree. The diagonal straight lines were simply added for comparison and do not indicate the position of the results otherwise. The Roman numerals at the ends of these lines denote the various plates, of which IV., V., and VI. were wrought iron, and the others in Fig. 83 were steel. The numbers 2 and 3 below the lines are placed to indicate the point of corresponding value on each line, because the diagrams overlap each other.

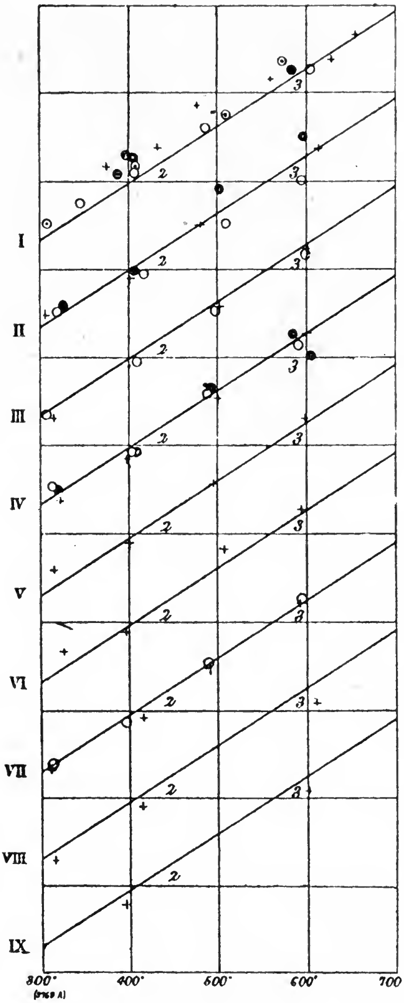


FIG. 83.

In the case of plate I. the mark + refers to the original plate, ● to the plate covered with mud or scale, ○ to the thickness of 10·5 millimetres, ⊙ to the thickness 7·5 millimetres.

In II., thickness of 28·7 mm. is indicated by +, 19·0 mm. by ○, and of 12·2 mm. by ●; in III., + = 30·5, and ○ = 30·5 mm., both surfaces crude; in IV., + = 29·0, ○ = 21·2, ● 20·9 mm., with upper surface turned, or in the third instance bright; V., + = 20·4 mm. turned; VI., + = 30·2 mm. both surfaces crude; VII., + = 15·6, ○ = 11·0 mm. turned at the upper surface; VIII., + = 11·5 mm. turned at the upper surface; IX., + = 18·2 mm. both sides crude.

With plate No. I. at a thickness of 30·5 mm. (1·2 in.), heat was

transmitted at temperatures $t = 374, 433, 468, 480, 489, 561, 628, 654, 674$ degrees C., at the rate of Q (kilog.-cals.) $= \frac{w \cdot 536}{t - 100} =$ 2·16, 2·39, 2·75, 2·74, 3·01, 3·15, 3·35, 3·63, 4·01 kilogramme-calories per hour per degree. The plate was then turned down on the upper surface until it was 10·5 mm. (0·41 in.) thick, and gave at temperatures $t = 346, 406, 484, 603$; Q = 1·74, 2·08, 2·59, 3·24. Again turned down to a thickness of 7·5 mm. (0·29 in.), it showed at $t = 308, 409, 503, 517, 573$; Q = 1·51, 2·14, 2·89, 2·63, 3·34. Finally reduced to a thickness of 5·4 mm. (0·21 in.), the lower surface having remained unchanged all the time, we have for $t = 319, 418, 499, 606$; Q = 1·54, 1·99, 2·58, 3·63. The experimenters do not claim an accuracy of more than $\pm$ 10 per cent.

The two copper plates experimented with had thicknesses of + = 29·5 mm. (1·16 in.), and ○ = 30 mm. (1·18 in.); the former was polished on the upper or inner side, the under side not being worked in any way. The results are shown in Fig. 84, the straight diagonal line being the same as in the iron and steel tests in Fig. 83.

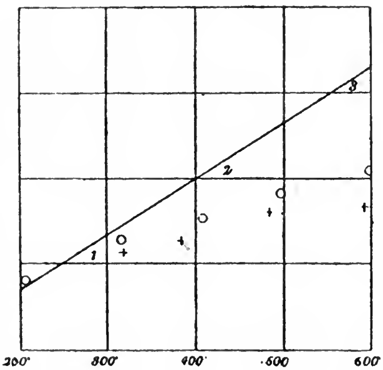


FIG. 84.

In these experiments, the thickness of the iron and steel plates and the state of their surfaces seemed to have scarcely any influence upon the heat transmission. The fact that the various points of the curves belonging to plates of different thicknesses lie close together, indicates that whatever may be the transmission resistances acting between the plate and the media on both sides of it, the resistance in the metal is insignificant for the thicknesses experimented with. "The temperatures t of the gases below the plate and 100° C., that of the boiling water above it, must widely differ from those of the surface layers of the iron. If there were no such differences, Q should be for thicknesses of 1, 2, and 3 centimetres, 300, 150, and 100

kilog.-cals., whilst in reality, the observed values of Q have varied between 1, 3, and 4 only; that is to say, have been small fractions of the calculated values."

Artificial incrustations did not seem to have much effect beyond increasing the time required to raise the water to boiling point. Afterwards, the amount of heat transmitted did not seem to be affected. "Plate I. was also tinned above; this had apparently an injurious effect. In order further to ascertain whether the condition of the lower surface exposed to the gases would have any influence, Plates II., now 12 mm. (0·47 in.) and V., 20 mm. (0·79 in.) thick, were fairly polished on both sides. The heat transmitted was unmistakably decreased. Between the temperatures $t = 311$ and 616, Q rose from 1·59 to 3·50, when the lower surface had not been touched and from 1·26 to 2·0 when that surface had been polished."

Although the position of the diagonal lines seems to correspond with Rankine's approximate formula, expressing that the heat transmitted is proportional to the square of the difference of temperature, it is pointed out that these experiments contain evidence that it is not safe to generalise from that empirical rule. "It does not hold for plates bright below, and certainly not in the least for copper plates." Copper transmits heat at the higher temperatures less rapidly than iron. On the other hand, iron and steel oxidise, and are more subject to gradual deterioration from this cause than copper. These points, no doubt, influence the above-mentioned transition-resistance, and further research is needed to investigate that portion of the subject.

One very important result of these experiments remains to be noticed, as it illustrates a point which has been repeatedly pressed in these pages, viz., the vital effect of movement of the hot gases. By altering dampers, etc., the same temperature of 400° C. was produced and maintained with an increased velocity of the ascending hot gaseous currents at each fresh experiment. In three tests under these altered conditions the evaporation was at the rate of 1·035, 1·086, and 1·098 kilogrammes of water per hour.

These experiments were subject to the same drawbacks as were those of Mr. Blechynden with regard to the application of the heat to the plate or dish containing the water, and the later

investigations of Miss E. M. Bryant, B. Sc.,[1] introduce some considerations based on the state of the surface of the plates, which also modify the result.

Bryant's Experiments.—Miss Bryant followed M. Hirsch in the form of apparatus employed, but introduced some important modifications, the use of fusible plugs being abandoned in favour of thermo-electric junctions embedded in the substance of the plates at different depths below the water surface, and in the hemispherical iron cup placed in the furnace. The heating was carried out by radiation from the inner surface of this metal cup, the gas flames from two Fletcher oxygen burners playing upon the outside of it within the fire-brick casing of the furnace. The dish containing the water, of which vessel the plate under test formed the bottom, was shielded against heating in any way but directly through the plate by means of a guard-ring consisting of an outer annular vessel B, made of sheet copper and containing water. Figs. 85 and 86 show the general arrangement of apparatus — the method of feeding the water was the same as in M. Hirsch's experiments. A is the inner vessel with the experimental plate for its bottom, the outer edge of the plate being insulated by means of a lining of asbestos or similar non-conductor in the space between A and B. The degree of heat to which the metal plates experimented with were exposed was necessarily limited by the temperature to which the hemispherical cup was raised; all the heat having, moreover, to reach the plates by radiation, as there could be no circulation of hot air or gases, except that of the very limited quantity of air in the hemispherical space enclosed. The Tables of results disclose that the temperature of the cup varied only between 600° and

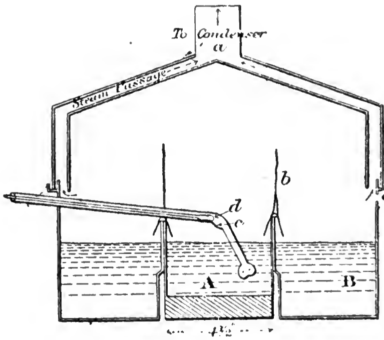


FIG. 85.

[1] Min. Proc. Inst. C.E., Vol. cxxxii., p. 274.

942° C., and was most frequently maintained at from 700° to 850° C., but these temperatures are considerably lower than those to which the iron or steel of boilers is exposed in actual work. Moreover, the transmission readings were not taken until the temperatures both of the plate and of the hot wall of the metal cup remained steady, but this showed only that the point of maximum rate of transmission for this apparatus, as it was arranged, had been reached. The velocity of the circulation of the water is an important element in the rate of transmission, because it is the water which carries off the heat which passes through the metal plate. Unfortunately, the shape and size of the circular vessel A were against anything but a very moderate speed and restricted kind of circulation, and consequently the maximum rate with such a vessel would not necessarily be the maximum rate of transmission with other arrangements. The fact of the heating being carried out almost entirely by radiation also gives a very limited range of value to these experiments, because such conditions are entirely artificial, and necessarily restrict the degree of heating. The paper of Miss Bryant itself contains evidence that when the hot gases were allowed to strike against the metal plate a much higher rate of transmission was reached. One Table (XLV.) records a series of experiments with a copper plate, in which the gases were allowed to strike directly on the plate, and the numbers of C.G.S. heat units transmitted per minute, which in the former experiments with radiation heating ranged from 3,820 to 8,540,

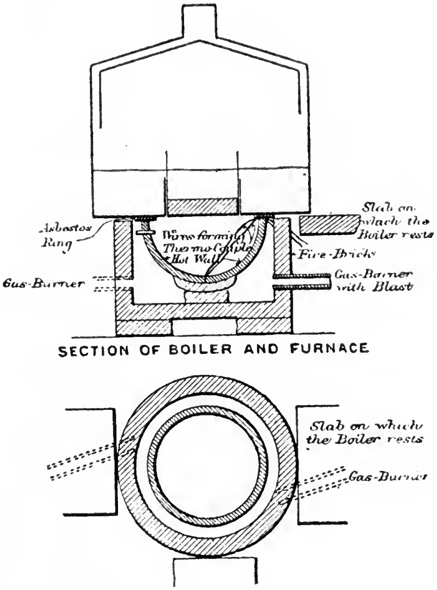
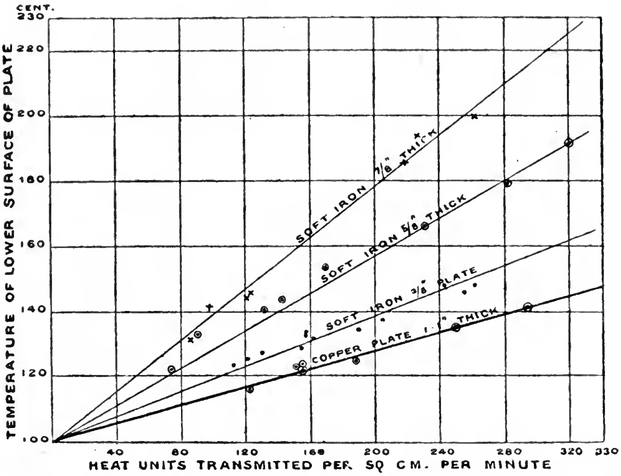
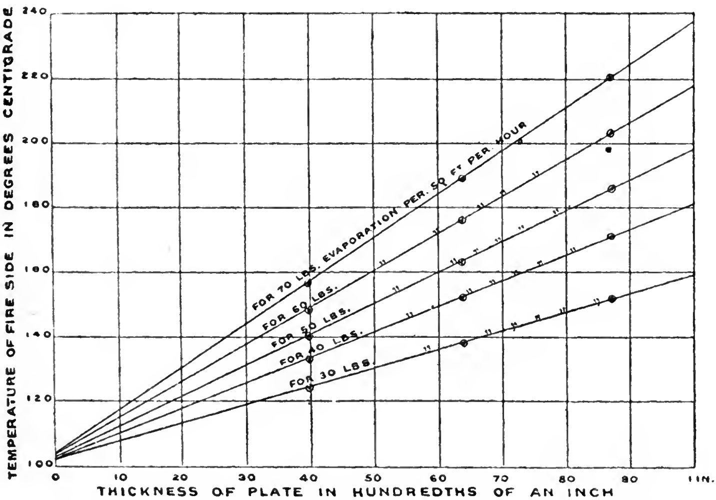


FIG. 86.



CURVES SHOWING THE TEMPERATURE OF THE FIRE SIDE OF THE PLATE AT DIFFERENT RATES OF EVAPORATION

FIG. 87.



CURVES SHOWING THE INCREASE OF TEMPERATURE OF THE FIRE SIDE OF THE PLATE WITH INCREASE OF THICKNESS AT DIFFERENT RATES OF EVAPORATION.

FIG. 88.

at once rose to from 4,700 to 16,050. Moreover, the paper contains the following significant remarks: "While the boiler was being heated before an experiment, a blast of air was sent into the hemispherical space below the plate. This prevented the hot gases from coming in contact with, and condensing upon, the cold iron, and thus prevented the rusting. This blast was stopped before the measurements were taken, as if left on it largely increased the circulation of air, and the result was an increase of evaporation for the same temperature of the hot wall." This may, of course, be read in either of two ways, but in view of the results given in Table XLV. we might be justified in taking the increased evaporation as the result of the increased circulation of air when the plate was hot. There is no manner of doubt that if movement of the water is essential to rapidity of heat transmission, movement of the hot gases is much more necessary and, moreover, a much more rapid movement is essential in this case. On this branch of the subject, however, Miss Bryant's experiments throw no further light.

The two preceding diagrams (Figs. 87 and 88) are given to show that in these experiments the temperature of the fire surface of the plate (through which heat is being transmitted to the water) increases directly as the rate of flow of heat through the plate, and also increases with the thickness of the plate when the rate of evaporation is constant. The water surface of the plate was found in these experiments to be between 3° and 12° C. above the boiling point of water. The results obtained with copper and steel plates are given in the succeeding Tables XLI. to XLV.

TABLE XLI.—COPPER PLATE. THICKNESS, 0·904 INCH = 2·3 CENTIMETRES. AREA, 96·3 SQUARE CENTIMETRES.

Date, 1895.			Temperature of Hot Wall in ° C.	Heat-Units Transmitted per Minute.	Lbs. of Water Evaporated per Square Foot per Hour.	C.G.S. Heat-Units per Square Centimetre per Minute.	Temperature of Water-Surface in ° C.	Temperature of Lower Surface in ° C.	Difference of Temperature between Upper and Lower Surfaces in ° C.	Duration of Experiment in Minutes.	Condition of Surface.
Nov.	7	I	759·5	4,220	10·0	43·9	102·6	107·0	4·4	20·0	Oxide.
„	7	II	770·0	4,680	11·1	48·6	102·6	107·1	4·5	12·0	„
„	12	I	820·0	5,170	12·3	53·7	...	...	...	28·5	„
„	12	II	723·0	4,090	9·9	42·5	103·6	108·0	4·4	20·0	„
„	13	I	769·0	6,970	16·6	72·3	105·0	111·6	6·6	17·0	Slightly blackened.
„	13	II	786·0	7,240	17·2	75·2	105·1	111·2	6·1	14·5	Slightly blackened.
„	15	...	627·0	3,820	9·8	39·7	104·0	106·8	2·8	24·0	Smoked.
„	18	I	746·0	6,260	14·9	65·0	106·8	112·1	5·3	30·5	„
„	18	II	773·0	6,890	16·4	71·6	106·7	112·5	5·8	31·5	„
„	18	III	787·0	7,510	17·9	78·0	106·8	112·7	5·9	22·0	„
„	19	I	807·0	7,990	19·0	83·0	107·2	113·2	6·0	15·0	„
„	19	II	825·0	8,540	20·3	88·6	107·8	113·8	6·0	15.0	„

TABLE XLII.—STEEL PLATE. THICKNESS 1·015 INCH = 2·58 CENTIMETRES. AREA, 105·4 SQUARE CENTIMETRES.

Date, 1895.			Temperature of Hot Wall in ° C.	C.G.S. Heat-Units Transmitted per Minute.	Lbs. of Water Evaporated per Square Foot per Hour.	C.G.S. Heat Units per Square Centimetre per Minute.	Temperature of Water-Surface in ° C.	Temperature of Lower-Surface in ° C.	Difference of Temperature between Upper and Lower Surfaces in ° C.	Duration of Experiment in Minutes.	Condition of Surface.
Nov.	30	...	775·0	8,780	19·1	83·4	107·0	139·8	32·8	26·0	Smoked and a little rusted.
Dec.	2	II	701·0	6,280	13·6	59·6	108·8	137·6	28·8	29·0	
„	2	III	750·0	7,180	15·6	68·1	109·0	141·0	32·0	23·5	
„	2	IV	773·0	7,420	16·5	70·4	109·6	144·1	34·5	9·0	
„	2	V	778·0	8,310	18·1	78·9	110·0	145·3	35·3	12·0	
„	4	...	796·0	9,090	19·8	86·2	107·9	147·5	39·6	24·5	
„	5	I	731·0	7,060	15·4	67·0	105·4	135·8	30·4	22·5	
„	5	II	648·0	4,815	10·5	45·6	103·9	125·8	21·9	13·0	
„	7	I	711·0	6,910	15·0	65·6	108·0	134·0	26·0	17·0	Rusted round the edges and smoked.
„	7	II	621·0	4,380	9·9	41·5	107·0	124·9	17·9	12·5	
„	12	I	834·0	9,640	21·0	91·5	108·1	143·2	35·1	18·0	Somewhat irregularly rusted and smoked.
„	12	II	841·0	9,820	21·3	93·2	108·1	144·8	36·7	22·5	
„	12	III	748·0	6,470	14·1	61·4	106·8	133·4	26·6	13·0	
„	13	I	766·0	7,450	16·2	70·7	105·2	135·0	29·8	33·0	Rusted chiefly at edges and smoked.
„	13	II	545·0	2,920	6·4	27·8	104·0	116·8	12·8	21·0	
„	14	...	793·5	5,460	11·9	51·9	106·5	131·0	24·5	16·0	Rusted slightly all over. No smoke.
„	16	I	807·0	6,040	13·1	57·3	105·5	129·9	24·4	31·0	
„	16	II	688·0	3,930	8·5	37·3	104·3	120·9	16·6	20·5	
„	17	I	834·0	7,380	16·1	70·1	104·7	134·8	30·1	32·5	
„	17	II	736·0	4,710	10·2	44·8	105·3	124·7	19·4	21·0	

TABLE XLIII.—STEEL PLATE. THICKNESS, 2·56 CENTIMETRES. AREA, 105·4 SQUARE CENTIMETRES.

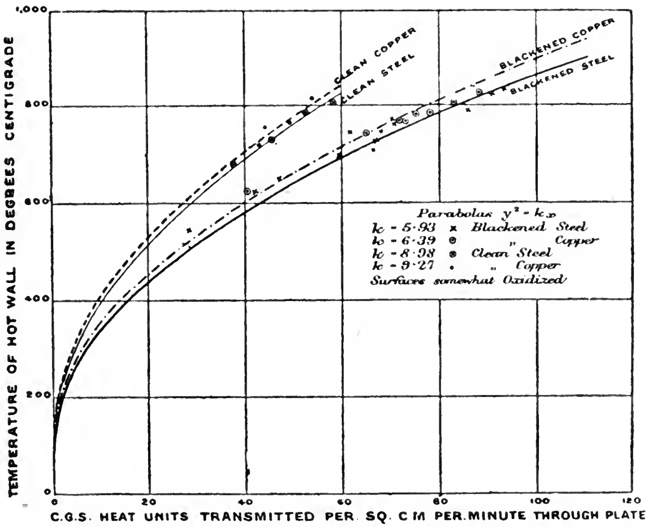
Date, 1896.			Temperature of Hot Wall in ° C.	C.G.S. Heat-Units Transmitted per Minute.	Lbs. of Water Evaporated per Square Foot per Hour.	C.G.S. Heat-Units per Square Centemetre per Minute.	Temperature of Water-Surface in ° C.	Temperature of Lower Surface in ° C.	Difference of Temperature between Upper and Lower Surfaces in ° C.	Duration of Experiment in Minutes.	Condition of Surface.
Feb.	20	...	942·5	6,581	14·3	62·96	104·9	135·0	30·0	20·0	Clean Surface throughout.
Jan.	31	I	887·0	6,698	14·6	63·57	108·4	136·0	27·6	26·0	
Feb.	7	I	869·0	6,287	13·7	59·67	107·0	134·5	27·5	34·0	
Jan.	27	...	860·0	6,172	13·4	58·58	105·6	130·3	24·7	21·0	
Feb.	21	I	854·0	6,219	13·5	59·03	105·5	132·0	26·6	20·0	
„	10	...	844·0	4,903	10·7	46·54	106·7	126·0	19·3	25·0	
Jan.	16	...	825·0	4,290	9·3	40·72	105·5	125·0	19·5	14·0	
Feb.	3	I	820·0	4,410	9·6	41·86	108·0	127·0	19·0	26·0	
„	21	II	776·0	4,711	10·2	44·71	105·5	126·6	21·1	21·0	
Jan.	30	I	747·0	3,441	7·49	32·66	107·0	123·8	16·8	34·5	
„	30	II	710·0	3,208	6·98	30·45	106·5	121·3	14·8	19·0	
Feb.	3	II	700·0	2,909	6·33	27·61	106·2	119·4	13·2	32·0	
Jan.	31	II	660·0	2,521	5·49	23·93	107·0	118·8	11·8	34·0	
Feb.	21	III	660·0	2,945	6·41	27·95	104·1	118·5	14·4	25·5	
„	7	II	584·0	2,119	4·61	20·11	104·4	114·6	10·2	32·5	
Jan.	29	...	781·5	4,315	9·38	40·96	107·5	128·0	20·5	25·5	

TABLE XLIV.—STEEL PLATE. THICKNESS, 2·56 CENTIMETRES. AREA, 105·4 SQUARE CENTIMETRES.

Date, 1896.			Temperature of Hot Wall in ° C.	C.G.S. Heat-Units Transmitted per Minute.	Lbs. of Water Evaporated. per Square Foot per Hour	C.C.S. Heat-Units per Square Centemetre per Minute.	Temperature of Upper Surface in ° C.	Temperature of Lower Surface in ° C.	Difference of Temperature between Upper and Lower Surfaces in ° C.	Duration of Experiment in Minutes.	Condition of Surface.
Feb.	11	II	927·0	10,644	23·1	101·03	107·0	154·0	47·0	9.0	Smoked.
„	11	III	871·0	8,944	19·5	84·89	107·2	145·4	38·2	9·5	„
„	11	I	834·0	7,732	16·8	73·39	108·2	142·2	34·0	22·0	„
„	12	II	656·5	4,507	9·5	42·78	105·8	128·1	22·3	27·5	„
„	12	I	603·0	3,755	8·2	35·69	105·0	123·0	18·0	20·5	„
June	8	I	815·0	7,366	16·0	69·90	106·7	136·7	30·0	23·0	„
„	8	II	753·0	6,158	13·35	58·42	106·2	133·5	27·3	9·0	„
„	8	III	622·0	3,715	8·05	35·24	105·0	121·6	16·6	23·0	„

TABLE XLV.—COPPER PLATE. THICKNESS, 0·904 INCH = 2·3 CENTIMETRES. AREA, 96·3 SQUARE CENTIMETRES.

Date, 1895.			C.G.S. Heat-Units transmitted per Minute.	Lbs. of Water Evaporated per Square Foot per hour.	C.G.S. Heat-Units per Square Centimetre per Minute.	Temperature of Water-Surface in ° C.	Temperature of Lower-Surface in ° C.	Difference of Temperature between Upper and Lower Surfaces in ° C.	Duration of Experiment in Minutes.	Condition of Surface.
Oct.	25	I	10,070	24·0	104.6	108·0	122·3	14·3	12·5	Smoked.
„	25	II	11,840	28·2	123·0	109·0	123·3	14·3	11·0	„
„	25	III	13,810	32·8	143·4	108·6	122·0	13·4	11·0	„
„	24	I	14,430	34·3	149·9	106·3	124·0	17·7	47·0	„
„	22	I	9,560	22·7	99·3	105·7	118·6	12·9	29·0	Not smoked.
„	22	II	6,550	15·6	68·0	104·9	114·6	9·7	12·5	„
„	21	I	10,680	25·4	110·8	107·8	119·8	12·0	11·0	Smoked.
„	21	II	4,700	11·2	48·9	106·0	112·3	6·3	40·0	„
„	17	...	12,110	28·8	125·7	107·0	118·1	11·1	30·0	„
„	16	...	9,590	22·8	99·6	105·0	114·8	9·8	36·0	„
July	23	...	15,320	36·4	159·0	104·6	120·1	15·5	12·0	„
„	23	I	14,140	33·6	146·8	106·2	119·0	12·8	14·0	„
„	23	II	16,050	38·2	166·7	106·5	120·6	14·1	10·0	„
„	25	I	15,040	35·8	156·1	105·4	118·7	13·3	23·0	„
„	25	II	...	...	...	107·1	121·9	14·8	22·0	„



CURVES SHOWING THE VARIATION OF HEAT TRANSMISSION WITH THE TEMPERATURE OF THE HOT WALL.

FIG. 89.

The curves in diagrams Figs. 89 and 90 have been plotted from these results, and the following are the remarks of Miss Bryant on them: "In Figs. 89 and 90 parabolas are drawn passing nearly through the points representing the results given in Tables XLI., XLII., and XLIII. and XLIV. respectively. It will be seen that all the results follow nearly the parabolic law

$$kH=(T-100)^2$$

where H is the number of heat units transmitted per square centimetre per minute, and T the temperature of the hot wall in degrees Centigrade.

"A comparison of the curves in Fig. 89 shows that, when both surfaces are blackened, for the same temperature of the hot wall the evaporation through the steel plate was greater than that through the copper, and thus the superior conductivity of the latter gives it no appreciable advantage in this respect. With surfaces covered with oxide the effects are nearly the same for the two plates, and the evaporation in both cases is much less than with blackened surfaces.

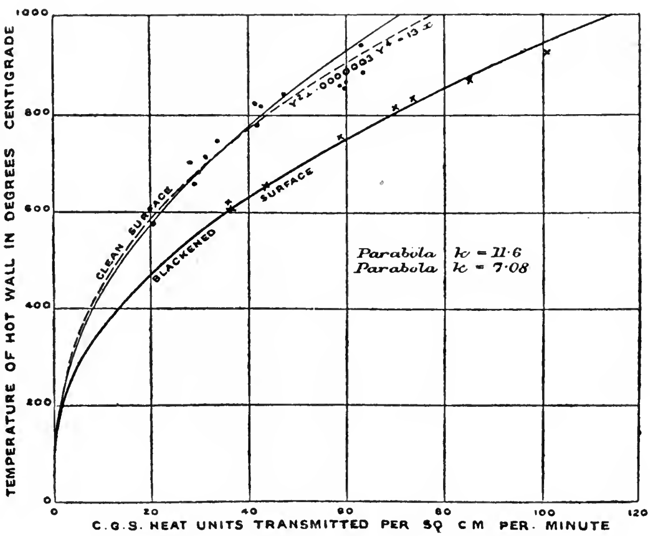


FIG. 90.

"A comparison is afforded in Fig. 90 between the effects of a clean and of a blackened surface exposed to radiation. Irregularities in the clean surface have caused the results to be somewhat irregular, but it will be seen that, while those for the blackened surface follow very nearly the parabolic law, those for the clean surface deviate considerably from it. In every case the evaporation increases somewhat more rapidly than it would if the parabolic law were exactly followed, and the author finds that Mr. Blechynden's results deviate from this law in an exactly similar way, although the mode of heating and the methods of measurement which he adopted were very different from those now described. With a blackened surface the heat is almost entirely supplied by radiation, and the curve is very nearly a parabola. With a clean surface the heat supplied by convection becomes relatively more important, and the deviation from the parabola is increased. An experiment arranged so that the hot gases acted directly on the plate showed a deviation from the parabolic law in the same direction and of very much greater amount. A possible explanation of this is that while the heat gained from radiation is proportional to the square of the difference of temperature between the surfaces, that due to convection is more nearly proportional to a higher power of this difference. Attempts to measure precisely the actual temperature of the gas when it strikes the plates were not successful. Any temperature between the highest in the furnace and one very near that of the surface of the plate, *i.e.*, about 160° C. could be obtained by placing a junction at different positions in the hot gas, and it was evident there was a layer of cold gas next the plate.

"A curious effect was noticed during the experiments. On several occasions when the vessel boiled dry, a sudden fall of the temperature of the plate, especially near its upper surface, occurred, followed by a rapid rise. The cooling is evidently due to rapid evaporation taking place when the water is nearly boiled away, and is followed by a rise of temperature as soon as the surface is dry."

These remarks confirm the opinion that in Mr. Blechynden's experiments the effects of convection in the heating were absent, on account of the impossibility of a proper circulation of the gases taking place in contact with the metal plate, and they show that if heating by convection had been properly carried out, the "parabolic law" would not have applied to his experimental results.

The "layer of cold gas next the plate" points to the fact that the circulation of the hot gases, in the case of Miss Bryant's experiment, was not sufficiently rapid. Some experiments were also made on the effect of oil on the water surface of the conducting plate, but the results obtained were not remarkable. The comparison made, however, between the fusible plug method and the thermo-junction method of measuring temperatures is of some importance. Plugs and thermo-junctions were inserted in the same plate, and their temperature indications were compared and found to be as follows :—

Temperature of Lower Surface of Plate.	
By Thermo-junctions.	By Fusible Plugs.
112·5° C.	About 123° C.
123·5° C.	Between 139° C. and 149° C.
130·0° C.	Above 161° C.

Not only was it found that the fusible plugs gave records which were not consistent with themselves, by melting at different temperatures, but also they invariably showed a higher temperature than that of the plate.

For this reason the results of Sir A. (then Mr.) Durston's experiments are not here quoted in detail,[1] although they possess considerable interest, but chiefly in connection with the fire-tube class of boilers. It is extremely difficult to ensure a sufficient supply of water to the surfaces of flat tube plates, either vertical or horizontal, which hold a number of tubes through which flame and hot gas are passing—the same hot gases and flame also striking against the tube plate. There is a similar difficulty in getting an adequate circulation of water on the surfaces of the inner rows of horizontal fire tubes, especially those nearer the top, as the steam generated below must pass around these on its escape upwards. Hence, no doubt, flame tubes must become hotter than water tubes, and that either they or the flat tube plates become too hot for durability of tube joints, experiment and practice both show.

Zittenberg's Experiments.—Mr. Zittenberg[2] made similar experiments to some of Mr. Durston's, but measured the temperature

[1] They will be found recorded in Chap. II. [2] See *Engineering*, Vol. lv., p. 440

of the plate by maximum thermometers dipped in holes tapped almost through the whole thickness of the plate and filled with quicksilver. He found, with $4\frac{1}{2}$ inches of blast pressure on the fire, "an excess of $14\frac{1}{2}°$ C. at a steaming power of 35 lbs. per square foot, against an excess of 44° C. to 68° C. in the two experiments of Mr. Durston with a $\frac{3}{4}$-in. steel plate." No such differences as the latter should be found in the metal of properly constructed water-tube boilers at work.

Experiments on a Niclausse Water-tube Boiler.—The most recent experiments of a similar kind to the foregoing, and probably the only ones hitherto made with a water-tube boiler, are those carried out by the Messrs. Niclausse on one of their boilers, and fully reported in a paper read at the Congrès de Mécanique at Paris in 1900. The boiler was composed of twelve rows of steel tubes, having in each row 10 tubes of 3·23 ins. (or 82 mm.) external diameter, and 6·35 feet (or 1·94 m.) long. The external surface of each row was 53·8 square feet (or 5 sq. metres) and the total heating surface of the boiler was $53·8 \times 12 = 645$ square feet (or $5 \times 12 = 60$ sq. metres). The grate area was 21·5 sq. feet (or 2 sq. metres) and the ratio of total heating surface to grate area was 30 to 1. The internal circulating tubes were each $1\frac{9}{16}$ inch (or 40 mm.) diameter.

For these experiments each horizontal row or storey (*étage*) of tubes was provided with distinct upcast and downcast passages to the steam and water drum and with a separate feed pipe, and the evaporation from each row was measured separately, the rows being numbered from 1 to 12 upwards, beginning with the row immediately over the fire. The calorimetric value of the coal used was 12·91 lbs. of water evaporated from and at 212° F. per lb. of coal and in each of the trials (lasting about eight hours each) nine different rates of combustion per square foot of grate with the same coal were employed, beginning with a minimum of 10 lbs. and going on to a maximum of 60 lbs. per square foot of grate per hour. The steam was evaporated in all the trials at atmospheric pressure from a feed-water temperature of 32° F. (or 11° C.). Both coal and water were carefully weighed, but neither the temperature nor the composition of the escaping gases was examined, the tests being merely to determine the relative amounts of evaporation from each row or storey of tubes at the different rates of combustion.

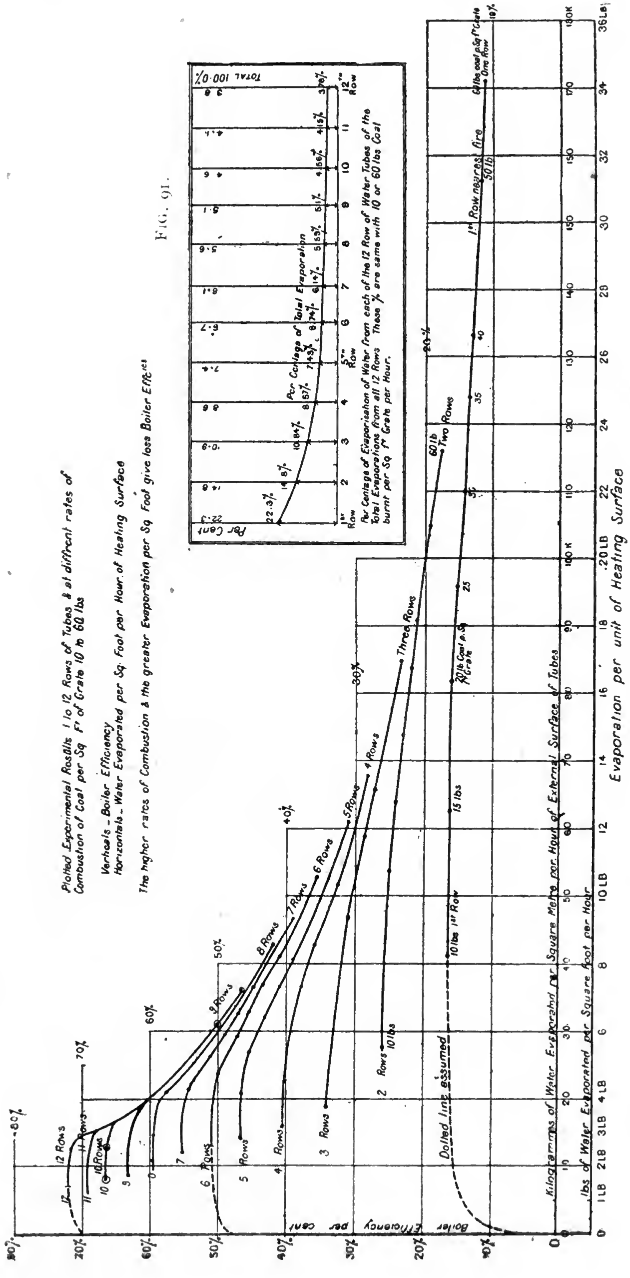

Plotted Experimental Results 1 to 12 Rows of Tubes & at different rates of Combustion of Coal per Sq Ft of Grate 10 to 60 lbs
Verticals _ Boiler Efficiency
Horizontals _ Water Evaporated per Sq. Foot per Hour of Heating Surface
The higher rates of Combustion & the greater Evaporation per Sq Foot give less Boiler Efficiencies
Per Centage of Total Evaporation
Per Centage of Evaporation of Water from each of the 12 Row of Water Tubes of the Total Evaporations from all 12 Rows These % are same with 10 or 60 lbs Coal burnt per Sq Ft Grate per Hour.
TOTAL 100·0%
Dotted line assumed
Boiler Efficiency per cent
Kilogrammes of Water Evaporated per Square Metre per Hour of External Surface of Tubes
lbs of Water Evaporated per Square Foot per Hour
Evaporation per unit of Heating Surface
1st Row nearest fire
Two Rows
Three Rows
12 Rows
11 Rows
10 Rows
9 Rows
8 Rows
7 Rows
6 Rows
5 Rows
4 Rows
3 Rows
2 Rows
60 lbs coal p. Sq Ft Grate One Row

FIG. 91.

FIG 94.

The following were the rates of combustion employed :—

50 75 100 125 150 175 200 250 300 kilos of coal per sq. metre of grate surface per hour, or

10 15 20 25 30 35 40 50 60 lbs. coal per sq. ft. grate surface per hour.

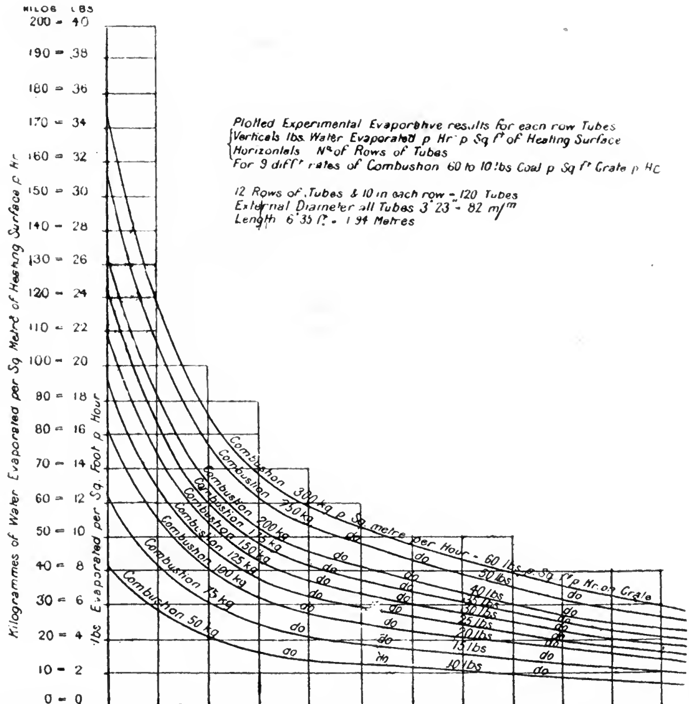
A remarkable feature of the results is found in the fact that the percentage of the total evaporation yielded by each of the twelve rows remained the same, whether 10 lbs. or 60 lbs. of fuel were burned per square foot of grate area per hour. This showed that the relative value of each row for evaporation was a fixed quantity.

The results are set out in the curves in diagram, Fig. 91, which gives the plotted results of evaporation from each row in percentage of the total evaporation from the twelve rows. The first three rows nearest the fire, with 161 sq. feet of heating surface, gave 47·94 (nearly 50) per cent. of the total evaporation from 645 sq. feet ; the remaining 52·06 per cent. required three times that amount of surface as provided by the remaining nine rows. Diagram Fig. 92 gives the evaporative rates for each row of tubes in lbs. of water per sq. foot of heating surface per hour for the nine different rates of combustion, the vertical scale representing the pounds of water evaporated and the horizontal the number of each row of tubes. The first row, nearest the fire, evaporated from a minimum of $8\frac{1}{4}$ lbs. of water per square foot of heating surface per hour to a maximum of $34\frac{1}{3}$ lbs. ; whilst the twelfth row evaporated only from $1\frac{1}{2}$ lb. to a maximum of 6 lbs. per square foot per hour.

Diagram Fig. 93 shows the heat efficiency for each row of tubes and for the different rates of combustion. The vertical scale on the left gives lbs. of water evaporated per lb. of coal, and that on the right the percentages of heat efficiency, whilst the horizontal scale shows the numbers of the rows of tubes. The curves give the results for the different rates of combustion in lbs. of coal per square foot of grate. The 100 per cent. line coincides with the calorific value of the coal. It is apparent that the lowest rate of combustion, viz., 10 lbs. per square foot of grate area per hour, gives the highest heat efficiency with this boiler, and that the efficiency is lowest at the highest rate of combustion.

Diagram Fig. 94 gives the plotted results on a base line

of lbs. of water evaporated per square foot of heating surface per hour, with the heat efficiencies of the boiler as a vertical scale. In this way the efficiencies can be read off and compared with different evaporative results. The curves represent



Nº of Rows of Tubes		1	2	3	4	5	6	7	8	9	10	11	12
Proportion of Heat9 Surface to Grate Surface		2.5	5 0	7 5	10 0	12 5	15 0	17 5	20 0	22 5	25 0	27 5	30 0
Heating Surface	Sq Metres	5	10	15	20	25	30	35	40	45	50	55	60
	Sq Feet	54	107	161	215	269	322	376	430	484	538	591	645

FIG. 92.

the results obtained from the different rows of tubes and for the different rates of combustion. The dotted lines to the left are assumed so that at zero evaporation there will be zero efficiency.

The general result with this boiler is that all the lines of

heat efficiency decrease with the higher rates of combustion, and are lowest with the highest rates of evaporation. The experiments, however, show that an evaporation of 34 lbs.

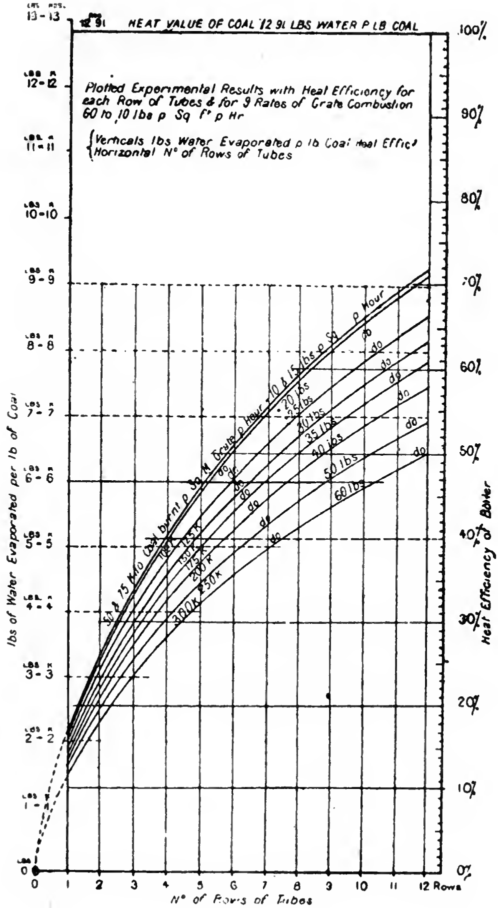


FIG. 93.

of water per square foot of heating surface per hour is obtained without injury to the tubes.

Row's Experiments.—The experiments carried out by Mr. O. M. Row, and communicated by him to the Manchester

Association of Engineers (27th February, 1897), show the remarkable effects of the indentations of the "Row" tube upon the efficiency of heat-transmitting surface. In several experiments the time required to transmit a given amount of heat from steam to water was one-half of that required in the case of plain cylindrical tubes of exactly the same heating surface. In order to ensure the employment of the same area of heating surface, the same tubes, which had first been tested as plain tubes, were afterwards indented and then tried under identical conditions in their new form.

The increased effect has been ascribed to a "scouring action" due to the form of the indented tube, which prevented the adherence of steam bubbles to the surface, and whilst that is probably true there seems little doubt that additional velocity is imparted to the movement of the currents in consequence, not only of frequent changes of direction, but also of the fluids being compelled to assume the form of comparatively thin films in contact with the heating surfaces.

Movement of Hot Gases.—Sir A. J. Durston made a series of measurements of the temperatures at various points in the travel of hot gas in a flame-tube boiler, commencing at the combustion chamber, and then at successive intervals of length inside some of the tubes, up to the smoke box. These measurements were made with a Le Chatelier electrical pyrometer and are shown in the following Table and curve (Fig. 95), which gives the mean results of eight sets of records.

Table XLVI.

	Degrees Fahr.
Temperature in combustion chamber	1644
„ just inside tube	1550
„ in tube 1 inch from combustion chamber	1466
„ „ 2 „ „ „	1426
„ „ 3 „ „ „	1405
„ „ 4 „ „ „	1412
„ „ 5 „ „ „	1398
„ „ 6 „ „ „	1406
„ „ 7 „ „ „	1400
„ „ 8 „ „ „	1410
„ „ 1 ft. 2 ins. „ „	1368
„ „ 1 „ 8 „ „ „	1295
„ „ 2 „ 8 „ „ „	1198
„ „ 3 „ 8 „ „ „	1106
„ „ 4 „ 8 „ „ „	1015
„ „ 5 „ 8 „ „ „	926
„ „ 6 „ 8 „ „ „	887
„ in smoke box „ „	782

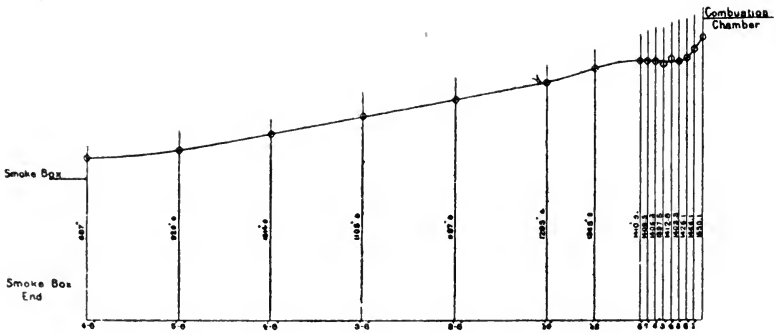


FIG. 95.

Another curve, slightly different in form, will be found recorded in Sennett & Oram's work "On the Marine Steam Engine" (Fig. 15, p. 41); see also Fig. 96. The boiler used in these experiments was the ordinary marine Scotch or cylindrical boiler in Keyham Yard. It had two furnaces (3ft. 6in. diameter) and 166 return tubes $2\frac{3}{4}$ins. outside diameter and 6ft. 8in. long, measured to the outsides of the tube plates. The boiler was worked at its normal capacity, the consumption of coal being about 17 lbs. per square foot of grate. Sir A. J. Durston's Paper contains no information as to the quantity of hot gases escaping per minute, but as on a total grate area of, say, 46 square feet, there were $46 \times 17 = 782$ lbs. of coal burned per hour, or $\frac{782}{60} = 13{\cdot}2$ lbs. burned per minute, on the supposition that 18 lbs. of air were supplied per lb. of coal, we can arrive at an idea of the volume and velocity of the gases by means of Rankine's rule, quoted in Chap. III., p. 63. The total area of the return tubes at $2\frac{1}{2}$ ins. inside diameter was $4{\cdot}9087 \times 166 = 814{\cdot}84$ square inches, and therefore it appears that, taking the temperature of the gases at either the highest or the lowest temperature in the tubes, the velocity in feet per second must have been very low (apart from their probably being throttled by the pyrometer in the tubes actually tested), and on that account the transmission of heat must have been at a low rate also. Moreover, the tube surface in this form of boiler is robbed of its efficiency by being placed right in the path of all the steam generated from the surface of the furnaces. The Table also shows that the gases did not flow through the tubes in straight steam lines, undulations of temperature being recorded at from three to four inches, five to six inches, and seven to eight inches.

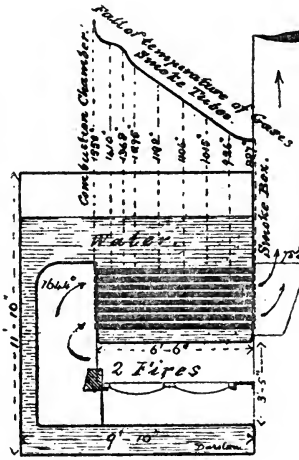
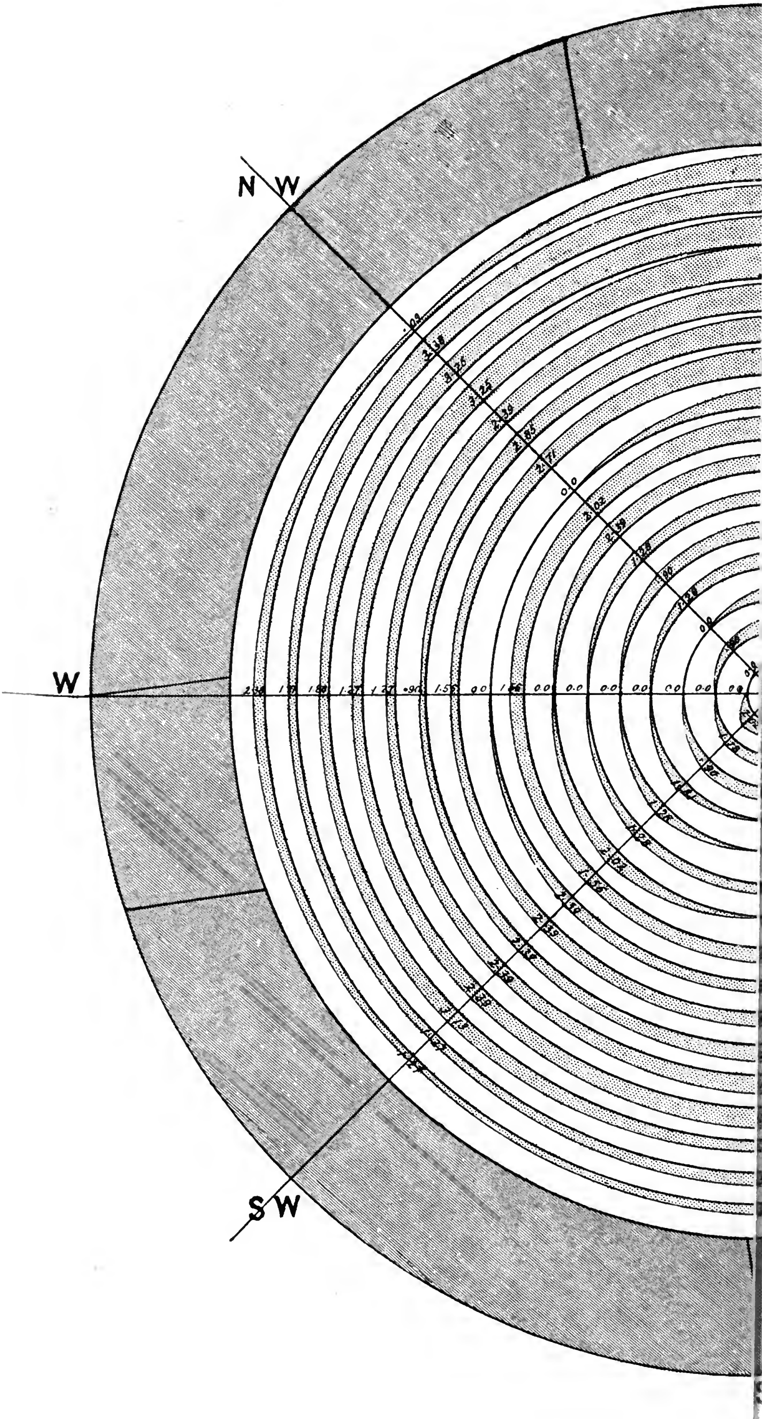
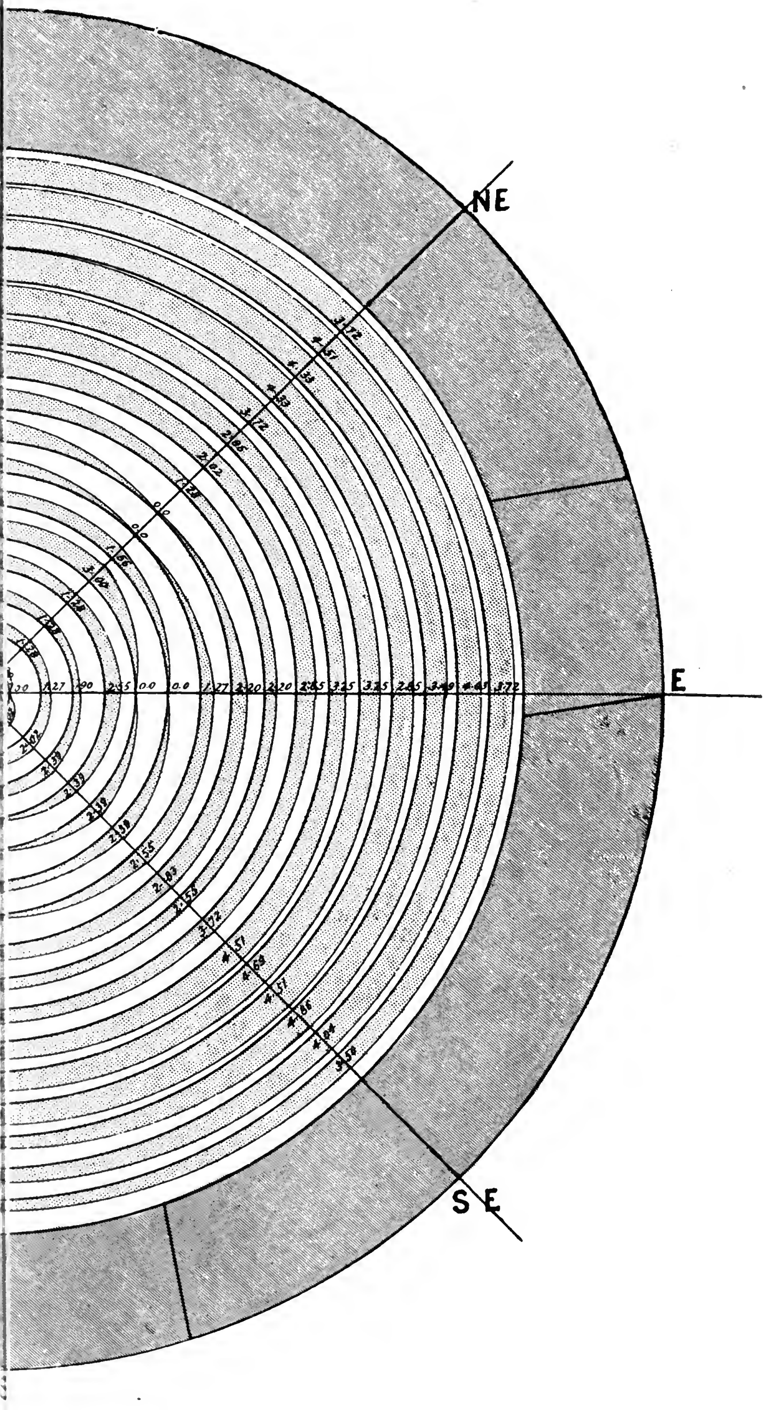


FIG. 96.

It has been ascertained from investigations of the movement and velocity of chimney gases, that the motion of hot gases, while proceeding along passages which introduce the elements



N W
W
S W



NE
E
SE

of friction and of changes of temperature, assumes the form of a spiral vortex. The vortex movement may also be seen when either heated gas or steam is allowed to escape into a cooler atmosphere. It has often been noticed that the smoke escaping from the top of a tall chimney moves not in straight lines, but in curls, which have the shape of vortices. See Fig. 97. Combined with this, in Mr. Mactear's results[1] the point of greatest speed was found at a less distance from the outside of a flue or chimney than one-third of the radius, which Péclet indicated as the point of greatest speed. It would follow from this that by adopting a spiral form of flues or passages for the hot gases, there would be no difficulty in obtaining sufficient movement to prevent any stagnation of gases at the surfaces of the tubes.

"Layers" of Gases.—The idea of a layer of cold, or rather of cooled, gases *adhering* to the heating surface of boilers, advanced by Miss Bryant and other investigators, is contrary to known laws of the diffusion of gases. If cooled gases are delayed by eddies or otherwise in contact with the metal, long enough to interfere appreciably with heat transmission, this only shows that greater movement or agitation of the gases is what is wanted. For philosophic discussion of the subject of heat transmission between gases, solids, and liquids, it may be advisable to imagine a series of layers of almost infinitesimal thinness, as has been done by Fourier and by Lord Kelvin, and, following them, in Mr. Halliday's recent paper.[2] But there is danger in allowing such a "mental picture" to occupy the place and attain the importance of an acknowledged fact. It must not be forgotten that in this matter we are dealing with molecular vibrations of some sort (about which, however, we know very little beyond the fact that there are such vibrations) passing through different media which are in intimate contact with one another. In traversing media with different degrees of molecular mobility—such as solid, liquid, and gas—there are probably differences in the period of the vibrations, or there is a period peculiar to each substance, and the change from one period or frequency to

[1] See Mills and Rowan "On Fuel and its Applications," pp. 379, 380; also Reports on the Examination of Chimney Gases, Alkali Manufacturers' Association, 1876-1877.

[2] Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xlii. p. 41.

another may introduce some resistance or loss. But if the movement can be transmitted through a comparatively rigid body, like iron, with an almost inappreciable resistance, it ought to be possible to transmit vibrations of the same nature between different substances in intimate contact without any considerable loss. It is, however, urged that "a film of cooled gases" does not correctly describe the state of affairs. "Was it not better to say," said one author, "the adhesive film almost infinitesimally thin, varied in temperature from the temperature of the plate on one side to that of the gases on the other, which would probably be from 400° to 2500° F. in the thickness of a bit of paper." But this really alters the matter very little, because in it there is an "adhesive film" which has the temperature of the plate at one face, whilst immediately outside of that there may be a temperature 2000° higher. That is certainly a very near approach to "a film of cooled gases"—it merely alternates the film, but not the idea. There are, however, some explanations given to us: "Although there is an adhering film of gas it is not quite evident that the same particles of gas will form that film. It is hardly to be expected that this will be so, when there is constantly rolling against this film of gas, gas of the same kind greatly agitated. The fire side of the film will hardly be defined, there may be breaches into it, and there will be diffusion, and if the theory of heat is correct, there will be a constant interchange of particles. That being so, and the velocity of the particles being as the square of the temperature, there will be an average effect which should be greater than that expected from a simple rise of temperature."

It will certainly occur to many that there is no reason why the diffusion by interchange of particles should have an arbitrary limit, and why the fresh particles of gas should not "roll against" the metal surface itself instead of stopping at the "adhering film" which only consists, after all, of gas of the same kind as that which is "rolling." If the rolling, or interchange of particles, or diffusion, proceeds as far as we maintain it does, that is, as far as the walls of the chamber confining the gas, there is then no probability of the existence of "an adhesive film" of gas, and the only valid explanation of slow conduction of heat from hot gases to metal is that of slowness of movement of the gases—always adding the possibility of resistance, due to

alteration of the frequency of vibrations. The same view holds good as to the water side of the plate, but because the rate of movement required for the water is not so great as that required for gases, better results have been reached with it, as we have seen. The good results obtained with steam as the heating agent, instead of fire gases, may be accounted for on similar grounds. It has been possible to reach with ordinary apparatus the velocity required by the steam, this being less than that required by highly heated and therefore expanded gases of less specific heat and less density than the steam.

Diagrams such as the one published by Mr. Halliday ("Steam Boilers," p. 50, fig. 20), or the one shown by Professor Watkinson (Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xli., pp. 58, 59), are misleading, because they do not properly represent the actual facts. (See also Trans. Inst. Engineers and Shipbuilders, Vol. xli., p. 130.)

There is not a loss of heat corresponding to the drop of temperature represented by the diagrams, nor is that drop a proof of great resistance. Apart from the great difficulty of correctly measuring the changes of temperature in the portions of gases or water immediately beside the iron surfaces, the diagrams cannot discriminate between the quantity of heat passing, and the actual temperature at the point measured. It has been shown by M. Hirsch that an evaporation of 75 lbs. of water per square foot of surface per hour need not cause a difference of temperature between the surfaces of the plate of more than 300° F. even with his apparatus, and an evaporation of 140 lbs. per square foot per hour has been carried on with a difference of only 107° F.[1] under specific conditions. The truth is that the actual temperature of the metal is, practically, a static condition, whilst the flow of heat is a dynamic process and the diagram cannot properly represent both. Regarding these differences of temperature, Lord Kelvin has said (Article "Heat" Encycl. Brit., 9th Edtn.), "Although the water or air at the very interface of its contact with the metal is essentially at the same temperature as the metal, there must be great differences of temperature in very thin layers of the fluid close to the

[1] This was the temperature difference between steam (used for heating) and water, and therefore that of the iron surfaces could not have been so high. (See Table at p. 138). Compare also Professor Witz's result on p. 216 following.

interface when there is a large flux of heat through the metal, and the temperature of the fluid, as measured by any practicable thermometer, or inferred from knowledge of the average temperature of the whole fluid, or from the temperatures of entering and leaving currents of fluid, may differ by scores of degrees from the actual temperature of the solid at the interface." As the commencement and ending of these remarks are, however, in apparent conflict, it is probable that Lord Kelvin meant at starting to say that portions of the fluid were *momentarily* at the temperature of the iron at the surface. The fact that both gases and water are in rapid motion (the more rapid the better) would prevent the arrangement of either into "layers," the actual formation of which would demand totally different conditions. It is important that Lord Kelvin admits that the temperature of the fluid may differ by scores of degrees from the actual temperature of the solid at its surface when there is a large flux of heat through the metal.

Comparison of Heat Transmission with Electrical and Magnetic.—Perhaps the clearest view of the action is afforded by a comparison with the analogous cases of electricity and magnetism. It is well known that the law in these matters is $C = \frac{E}{R}$, or current (quantity) $= \frac{\text{electromotive force,}}{\text{resistance ;}}$ or for magnetism $\phi = \frac{M}{R}$, and, as in the case of heat we are dealing with allied molecular vibrations, it is reasonable to expect that the conditions here should be similarly expressed, viz., $Q = \frac{T - T^1}{R}$,

Q being the quantity of heat flowing, measured in heat units.

$T - T^1$ being the difference of temperature which causes the flow, and thus answering to the difference of potential in the electrical circuit ; and

R being the sum of the resistance opposed to the flow of heat. In one respect such heat measurements are much less complete than those of electricity, and that is in the fact that no proper measure or expression of this resistance (to correspond to the ohm in electrical measurements) has been as yet arrived at. Consequently, in dealing with the transmission of heat in boiling or steam raising, the conditions of the action have been variously

expressed. There is this difference between the action here and that in electrical matters that, whereas the resistance to the flow of electrical current is wholly a question of the condition of the wire or metallic current, in the transmission of heat, resistance may be due to the condition of the metal plate, and also may be in great part due to the want of proper conditions in the fluids which form part of the circuit. It has been customary to class these different causes of resistance under the heads of the *internal* thermal resistance of the plate and the *external* thermal resistance, but to confine these too much to a question of the plate and its surfaces. Rankine says: "The rate of external conduction may be expressed by dividing the difference of temperature by a coefficient of *external thermal resistance*, depending on the nature of the substances and also on their temperatures"; but it is evident, from what we have been considering, that this expression must also be made to bear some relation to the *velocities* of movement where air or hot gases, or steam or water, are concerned in the action.

The difficulty is not to get the heat to pass from the fluid to the iron, or *vice-versâ*, but it is to keep the fluids in the best condition for the maximum flow of heat.

Professor Perry's Formula.—Following Professor Osborne Reynolds' theoretical forecast, Professor Perry[1] has recently suggested a general symbolic representation of the theory of transmission in fluids. Let average velocity be V, average temperature (absolute) of gases be T, and average temperature of metal plate be T_0. Suppose a layer of fluid at rest at the surface of the metal of a flue. Per unit area per second let N molecules enter this layer, giving to it axial momentum per second proportional to NV. This is what is meant by force of friction F per unit area; so that $N \propto \frac{F}{V}$.

Now, each molecule brings with it kinetic or heat energy proportional to T, and takes away energy proportional to T_0.

Neglecting heat resistance between layer and metal, the heat per second per unit area brought to the metal is $H \propto N\ (T-T_0)$ or $H \propto \frac{F}{V}(T-T_0)$.

[1] Trans. Inst. Eng. and Shipbuilders in Scotland. Vol. xlii. Part I., 25 Oct., 1898. Prof. Perry's remarks did not appear until this chapter had been written up to this point.

Now, in fluids $F \propto \rho V^2$ where ρ is the density, and hence in gases H is proportional to V.

The weakness of this expression of the theory, Professor Perry remarked, lies in the use of *average* V and T, but there can be no question as to its importance.

Professor Perry also remarked that, at present, the metal resistance was $\frac{1}{100}$th or $\frac{1}{1000}$th of the whole heat resistance, but he thought it possible to get nearly to the condition in which the metal resistance would be the most important heat resistance. In that case it is apparent that the phenomena of heat transmission would be strictly comparable with those of electrical transmission.

Professor R. H. Smith's Formula.—Of the various formulæ proposed in connection with this subject, that of Professor R. H. Smith[1] sought to express the relation between heating surface, boiler power, and boiler efficiency. The following is an outline of his examination of the subject and of some of his terms :—

B.H.H.P.=Boiler heat H.P.=Thermal units per hour delivered to the water $\times 772 \div 1{,}980{,}000$ (*i.e.*, $60 \times 33{,}000$=the number of foot pounds per hour required to supply energy at the rate of 1 H.P.)= the heat H.P. of the boiler.

The latent heat of evaporation of 1 lb. steam from and at 212° F. = 900 ; then 1 B.H.H.P.$=\dfrac{1{,}980{,}000}{966 \times 772} = 2{\cdot}65$ lbs. of steam evaporated from and at 212° F.—*i.e.*, the evaporative power as usually stated $\div$ 2·65, gives the strictly definite measure of the steaming power of the boiler in H.P. units. The average of fairly good boilers and engines gives 1 B.H.H.P.=10 I.H.P.

At the rate of 15 lbs. water per I.H.P. per hour we should have 5·66 B.H.H.P. per I.H.P.

At the rate of 30 lbs. water per I.H.P. per hour we should have 11·32 B.H.H.P. per I.H.P.

At the rate of 45 lbs. water per I.H.P. per hour we should have 16·98 B.H.H.P. per I.H.P.

At the rate of 60 lbs. water per I.H.P. per hour we should have 22·64 B.H.H.P. per I.H.P.

[1] See "Industries," Vol. iii. (1887), pp. 1, 27, 413.

B.M.H.P. = Boiler mechanical H.P. = the actual amount of mechanical work done in foot lbs. per hour by the water as it evaporates and expands into steam ÷ 1,980,000. If V cubic feet of steam be evaporated per hour at absolute steam pressure = P lbs. per square foot, then

$$\text{B.M.H.P.} = \frac{PV}{1,980,000}$$

Ratio of the B.H.H.P. to B.M.H.P. for different steam pressures :—

Absolute steam pressure in lbs. per sq. inch.	$\frac{\text{B.H.H.P.}}{\text{B.M.H.P.}}$
10	15·8
25	15·1
50	14·6
75	14·35
100	14·15
125	14·05
150	13·95
175	13·85
200	13·80
225	13·75
250	13·70

NOTE.—The ratio is less for high than for low pressures, but the whole variation is very small, being 15 for about 15 lbs. above atmosphere, and more than 13·6 for 300 lbs. above atmosphere, no account being taken of the effect of priming, which would increase the ratio.

The B.H.H.P. depends, first, on the amount of heat generated per hour by the combustion of the fuel ; and, secondly, on the proportion of that heat extracted from the furnace gases and transmitted to the water. The heat obtained from combustion depends necessarily on the quality of the fuel and on the completeness of the combustion ; and Professor Smith took as an average value 14,000 heat units or 10,810,000 foot lbs. per lb. of fuel ; 11,000,000 foot lbs. or 14,250 heat units being taken as a maximum for high-class coal and 10,000,000 foot lbs. or 12,950 heat units as a minimum for poor fuel.

Measuring the rate of heat generation in horse-power and calling it furnace horse-power, or F.H.P., it appeared that every F.H.P. required $\frac{1,980,000}{14,000 \times 772} = \cdot 183$ lb. of fuel per hour.

The proportion of the heat so generated that is transmitted to the water, or the ratio $\frac{\text{B.H.H.P.}}{\text{F.H.P.}}$, expresses the boiler efficiency in view of the heat utilisation. Professor Smith admits that the efficiency so expressed ranges from 50 per cent. to a little over 90 per cent., and that it increases with the length of heating surface over which the hot gases have to travel before escaping to the chimney. It is, of course, affected by losses from radiation, conduction, etc.; but, according to Professor Smith, it is increased by every effective means taken to mix the various currents of gases thoroughly together, so that the hot currents may be brought into close proximity to the plates and the colder currents withdrawn quickly into the parts of the flues more remote from the heating surface.

In calculating the rate at which the gases cool, by giving up their heat in passing from furnace to chimney, Professor Smith remarks, "We must do so from the average temperature over the whole flue section. We equate this to the rate of conduction through the plates, using a coefficient of conductivity q per square foot per hour; and whether we use Péclet's, Rankine's, or any other formula for q, that value refers to a surface difference of temperature between gas on the one side and water on the other side of the plates. We must, therefore, allow for the difference between surface and average gas temperatures, by taking a smaller q than would correspond by the formula to the average. This lessening of the effective conductivity increases with the difference between surface and average temperatures, and, therefore, increases with the size of the tube, other things being equal." "Taking all these three equalising agencies (mechanical mixture, radiation, and conduction) as equally active in large and small tubes, it is evident that the excess of the average over the surface temperature increases with the size of the tube. The measure of the excess, other things being constant, may fairly be taken as the ratio of the volume of gas in the flue to its surface. This ratio equals the 'hydraulic mean depth' of the flue, being one-fourth the diameter for round and one-fourth the side for square tubes. On this account, the boiler efficiency may fairly be considered as less than that reckoned on the supposition of uniform temperature throughout each flue section, by an amount, roughly, at least proportional to the

reciprocal of the hydraulic mean depth of the main flues."[1] "This does not mean," adds Professor Smith, "that the efficiency is inversely proportional to the hydraulic mean depth. If e' be the efficiency calculated for uniform distribution of temperature; d the hydraulic mean depth of the flue or tube; and c a constant at present not known, but which is not so small as to be unimportant; then the true efficiency would be

$$e = \frac{e'}{1 + cd}\text{"}$$

In connection with this subject, Professor Smith points out that although the change from large flue section to small brings the surface gas temperature more nearly to equality with the average, and thus, perhaps, increases the boiler efficiency, yet it introduces a large amount of frictional and viscous resistance to the passage of the gases through the flue, which resistance has to be overcome either by the chimney draught or by an equivalent furnace pressure supplied by a fan blast, and therefore it results in higher temperature of chimney gases. In this way "there is quickly reached a thermodynamic limit to the increased economy obtained by increasing the ratio of length to sectional perimeter of the flues."

By a series of steps or "rules," dealing with different elements of the subject, Professor Smith arrived at the following formula:—

$$\frac{S}{\text{B.H.H.P}} = \rho\gamma\{1 + 0{\cdot}08\,d\}\left\{\frac{1 - 0{\cdot}02\,n}{1 - 0{\cdot}0002\,nt}\right\}\left\{\frac{n^{1+2e}}{50(1-e)}\right\}$$

S being the heating surface in square feet;

ρ being a factor to allow for loss by radiation and conduction from the outside shell of the boiler and by incomplete combustion;

γ being a factor to allow for loss by diminution of conductivity by sludge and scaling, and sooting of the plates;

d being the mean hydraulic depth of the flues in inches;

n being the ratio of actual air-supply to that chemically required for complete combustion;

t being the excess of steam temperature over outside air temperature in degrees F.;

[1] *i.e.* their capacity ÷ their surface.

e being the furnace and boiler efficiency, *i.e.*, the ratio of heat received by water and steam to the heat generated by combustion in the furnace.

The factor 50 was chosen by reference to the experiments of Péclet on conduction from hot gas to water through an iron plate.

In calculating the heating surface required per B.H.H.P., Professor Smith said that "by assuming a steam pressure of 75 lbs. per square inch absolute, and certain efficiencies, and certain values of c ranging from 3 to 10, the following Table of heating surfaces required per B.H.H.P. has been calculated. It must be remembered that, taken per engine I.H.P., the required heating surface will be, on the average, ten times as much. Taken per B.M.H.P. it is fifteen times as much for very low-pressure, and fourteen times as much for high-pressure boilers. Certain allowances have also to be made as explained below."

TABLE XLVII.

HEATING SURFACE IN SQUARE FEET PER B.H.H.P.

	Boiler efficiency $\frac{\text{B.H.H.P.}}{\text{F.H.P.}}$				
	·9	·8	·7	·6	·5
C=·2+2·8n.	Heating surface square feet.				
3	·28	·113	·070	·053	·042
4	·627	·215	·133	·095	·076
5	1·494	·362	·219	·156	·120
6	Impossible.	·579	·328	·233	·177
7	...	·883	·479	·328	·253
8	...	1·315	·655	·447	·341
9	...	2·000	·902	·592	·448
10	...	3·212	1·210	·766	·577
Coal per hour per B.H.H.P. F.=·204		·23	·26	·305	·37

In the above, c = the total specific heat per F. degree of all the gaseous products of combustion of one pound of fuel, including

the unburnt excess of air and the inert nitrogen of the air. The "allowances" referred to are five in number and result in causing a considerable increase in the surface required from that shown by the plotted curve of these figures.[1]

Although Professor Smith gave effect to some of these in the complete formula quoted above, it appeared, from a later endeavour to apply the formula to the results of trials of a Thornycroft water-tube boiler,[2] that the calculation based on the hydraulic mean depth of flues did not fully apply to this class of boilers, and that the various factors could not fully represent the actual state of affairs. Moreover, Professor Smith's calculations take no account of the *intensity* of the combustion, which must exert a considerable effect on the rapidity of transmission, and the "boiler efficiency" term is, as usual, an expression only in view of heat utilisation apart from comparative dimensions of the boiler, so that it is not an expression of *heat efficiency per unit of heating surface.* It has also been remarked, as to Professor Smith's calculated results of the Thornycroft trials, that "the extent of surface actually needed to give the results of the lowest power trial was in excess of that given by the formula, when the constants were adjusted to agree with the highest power trial, in the ratio of 2·77 to 1·18, and the intermediate ones varied proportionately."[3]

Both Mr. D. K. Clark,[4] Mr. J. A. Longridge,[5] and Mr. M. Longridge[6] have proposed formulæ dealing with the proportions of locomotive boilers and their evaporation, but none of these has been found to embrace the rates of heat transmission with varying proportions in that type of boilers alone, and it is apparent that the wide differences in design in water-tube boilers render these formulæ even more inapplicable to them.

Mr. Hudson's Formula.—The only formula for heat transmission, including a factor for velocity of the hot gases, which

[1] See "Industries," Vol. iii., p. 28.

[2] Min. Proc. Inst. C.E., Vol. xcix., pp. 135–138, 145.

[3] Mr. J. G. Hudson in *The Engineer*, Vol. lxx. (1890), p. 449.

[4] Min. Proc. Inst. C.E., Vol. xii., pp. 382–449.

[5] Min. Proc. Inst. C.E., Vol. lii., pp. 98–176.

[6] Manchester Association of Engineers, January, 1890; refer also to Prof. R. Werner, Zeit. des Ver. Dent. Ingen. (1883), pp. 394–398, abs. in Trans. N. of E. Inst. M. Eng., Vol. 33, p. 77.

has been as yet proposed in anything like a complete shape, is given by Mr. J. G. Hudson, in his articles on "Heat Transmission in Boilers," in *The Engineer*, Vol. lxx., pp. 449, 483, 523. Mr. Hudson reasoned from the results of Mr. C. Lang's experiments (see p. 138 *ante*) on evaporation with steam heat, and from the figures given by Mr. Wm. Anderson (in Min. Proc. Inst. C.E 1883-84, "Heat Lectures") as to the probable temperature of the plates of a boiler over the furnace.

To cause the maximum evaporation given in Mr. Lang's results the total difference of temperature needed would, according to Mr. Hudson, be only $\frac{40 \times 1115}{1224} = 36{\cdot}4$ degrees. "The heating steam would therefore need a temperature of $340 + 36 = 376$ degrees, but the hotter side of the heating surface would be even cooler than this by the difference required to cause the transfer of heat from the steam to the surface." "Now," said Mr. Hudson, "in effecting the same rate of evaporation by fire heat instead of steam, the same amount of heat has to be transmitted, and there should be no change as regards the head or difference of temperature needed for the conduction of this heat through the thickness of the metal, nor for its emission to the water. The temperature of the metal will therefore remain unaltered." Here, however, Mr. Hudson assumes too much, as the experiments recorded in this chapter prove. Even taking Mr. Anderson's limit of the melting point of lead as showing the temperature to which the boiler plates have not been raised, there might still be a considerable rise in temperature above 376° F.

Mr. Hudson proceeds to say :- "It is not known what furnace temperature would be needed to effect the rate of evaporation assumed, but it would undoubtedly be high, probably not less than 2500° F. ; and it seems difficult to escape the conclusion that of the temperature difference of $2500° - 340° = 2160°$, no less than $2160° - 36° = 2124°$ or 98·3 per cent., plus the difference required in the case of steam, must be needed to effect the transfer of heat from the hot gases to the metal, the remaining $36° = 1{\cdot}7$ per cent., minus the same quantity, sufficing to carry the heat through the metal and into the water. The only loophole for substantial error in the above calculation would seem to

be the possibility that in a crowded boiler the movement of the water might be less active than in the steam evaporator, causing a larger difference to be needed for the emission. An extreme allowance for this would be to halve the rate of transmission, which would give the metal a higher temperature by less than 36 degrees."

Following this line of argument, Mr. Hudson proceeded to inquire in what relative proportions the total head of temperature should be allotted to the absorption, conduction and emission respectively, and proposed the following as a rough approximation : "In the first place, some idea of the head needed to overcome the internal resistance of the metal can be obtained for temperatures not exceeding 500° or 600° F. from the following formula, based, for wrought iron, on Forbes' experiments on the conducting powers of that metal, between 32° and 527°, and for other metals on Dispretz's data as to their relative conducting powers.

Q = Units transmitted per square foot per hour.

R = Rate of transmission for 1in. thickness, 1 square foot, 1 hour, and 1 deg. Fah. at 32 deg. = for copper 1243 units, brass 1044, cast iron 783, wrought iron or steel 522.

D = Difference in degs. Fah. required to overcome the internal resistance.

t = Thickness of the metal in inches.

T = Mean temperature of the metal.

Then—

$$Q = \frac{D \times R \times (1467{\cdot}5 - T)}{t \times 1435{\cdot}5},$$

and—

$$D = \frac{Q \times t \times 1435{\cdot}5}{R \times (1467{\cdot}5 - T)}$$

"For copper tubes of 10 B.W.G. thickness (as used in Mr. Lang's experiments) at the assumed duty, this formula gives 6 deg. as the head needed for the conduction alone. How the balance of 30 deg., available in the case of steam as the heating agent for the surface absorption and emission, should be apportioned, is of little moment for the present purpose. No doubt the steam side would need less than the water, and taking the ratio of 1 to 2, giving 10 deg. and 20 deg. respectively, the various temperatures would stand as follows :

	Steam.		Fire.	
Heating medium ...	376°		2500°	
Difference for absorption		10°		2134°
Surface, hotter side ...	366°		366°	
Difference for conduction		6°		6°
Surface, next water ...	360°		360°	
Difference for emission		20°		20°
Water in boiler	340°		340°	
Total difference ...		36°		2160°

"For an iron or steel plate ½ in. thick, the difference would be 55 deg. instead of 6 deg., requiring an important addition to the temperature, or involving a considerable reduction in the duty in the case of the steam, but only an unimportant variation in either respect for the fire. For lower rates of evaporation than that assumed, the differences would be divided out in very much the same way, except that the head needed for conduction would be even less in proportion."

Consistently with this reasoning Mr. Hudson concluded that "in evaporating by fire heat, the whole of the difference may, for all practical purposes, be taken as available for effecting the transfer of heat from the gases to the metal, and the latter may be considered as having the same temperature as the water." Also that, "however valuable an active circulation in a boiler may be, on other grounds, no activity beyond that needed for keeping water in contact with the heating surfaces can, by reducing the difference needed for emission, appreciably increase the quantity of heat transmitted, seeing that the amount of the difference capable of being influenced in this way is such a trifling fraction of the whole."

It cannot be maintained, however, that either of these conclusions is firmly established. Later experiments have shown that the metal has not the same temperature as the water, but, on the contrary, that the temperature of the fire surface of the plates bears a well-defined relation to the flow of heat through the metal and to the thickness of the metal when the rate of flow is constant. It has also been found that the velocity of movement of the water has a decided influence upon the rate of flow of

heat, and this, apart from questions as to the temperature of the plate, or the so-called emission or emissive power of the surface. The second of Mr. Hudson's conclusions is, in fact, at variance with his own subsequent remarks on the effect of velocity of movement, although in them he is mainly occupied with the movement of the gases. Still, he says, "in the case of heating water by steam, it can be conclusively shown that, other things being equal, the quantity of heat taken up by the water is almost wholly a question of the speed with which the latter traverses the heating surface, the transmission increasing only somewhat less rapidly than the speed. So important is this influence, that the transmission has been found to vary from as little as 20 or 30 units per degree, where the water was confined in small tubes and moved very slowly, up to nearly 1,000 units according to the speed." "Knowing this," Mr. Hudson proceeds, "it is natural to ask whether the speed of the gases in a boiler might not in like manner affect the activity of the transmission, and, the idea once started, much confirmatory evidence suggests itself, and the theory seems to account for much previously unexplained." It will be observed that Mr. Hudson speaks of heating water by steam, but it stands to reason that if movement of the water has been found to accelerate heat transmission with the moderate difference of temperature which that system of heating provides, it must be all the more necessary in presence of the much higher temperatures provided by fire gases. With regard to the necessity for rapid movement of the gases Mr. Hudson is clear and emphatic in the arguments which he advances in support of it, but is mistaken in the idea that the element of speed had not been previously taken into account as possibly affecting the transmission. Péclet, Craddock, Osborne Reynolds, Hagemann, and Louis Ser, at least, had previously shown the necessity for it and some of its effects experimentally. Nevertheless, among engineers, Mr. Hudson led the way in appreciation of its influence. "That the speed might, not unreasonably, be expected to affect the result in one direction or the other, it is natural to suppose," he remarked, "when the extent of its variation is apprehended. In a lightly fired Lancashire boiler it may be under 4 ft. per second, range from that speed up to 140 ft. in a locomotive, and reach considerably over 200 ft. in a loco. type torpedo boiler when hard pressed. The influence of the speed

seems to explain the following anomalies: (1) The injury to a boiler from the use of forced draught is almost invariably confined to overheating the tubes, though the fire-box plate surfaces are exposed to an even higher temperature. (2) The generally inferior efficiency of water-tube, as compared with fire-tube boilers. (3) The high efficiency of locomotive boilers, considering their small extent of surface in proportion to fuel burnt. (4) The comparatively high efficiency of boilers worked at extreme rates; thus the locomotive type torpedo boiler tested at Portsmouth had, in the highest duty trial with 6 in. draught, only the very small proportion of ·34 sq. ft. of surface per 1 lb. of fuel. The reduction of the gases with this small surface to 1444° corresponds with a transmission per degree several times greater than is attained by boilers working at more ordinary rates. (5) The slight increase in economy to be obtained by reducing the weight of fuel burnt in a given boiler below a certain point, changing at last to an actual falling off. An extreme example of this is found in the trials of a sectional boiler for the Kimberley Water Works, in which the evaporation from and at 212° was 10·87 lbs. with 3·64 sq. ft. heating surface per 1 lb. fuel, reached 11·5 lbs. with 6·44 sq. ft., and fell to 8·15 lbs. at the extreme proportion of 16·1 sq. ft. (6) The circumstance, of which many examples might be quoted, that the mischievous effect of an excessive supply of air is usually limited to the carrying to waste of little more than the extra heat corresponding with the extra weight of the gases, their temperature being nearly the same for all ordinary quantities; though if the transmission were proportional to the temperature merely, that of the waste gases would be considerably higher with the larger supply. An excessive air supply does not, as might at first sight be expected, result in a low temperature of the waste gases, unless the proportion of heating surface to fuel is so limited that the smaller volume of gases, originally hotter because of its smaller heat capacity, but therefore also more rapidly cooled, has not time to fall to the temperature of the larger, originally cooler, but more slowly cooling volume. The larger volume will, however, be found to transmit more heat per degree of difference, though it loses temperature more slowly, owing to its greater heat capacity, and it would appear that this greater transmission is due to the greater speed."

Mr. Hudson proposed the following formulæ and coefficients as embodying his conclusions on the whole subject. He said, "They are, of course, applicable only to surfaces in constant contact with water. For simplicity's sake, the transmission from the gases has been calculated step by step, for increasing intervals, as a formula representing the continuous action—if such could be framed—would unavoidably be too complex for convenient use." "The formula for fire-box transmission is unavoidably empirical and without a rational basis, as the transmission here could not be calculated on the difference of temperature as for the tubes, because in a fire-box the temperature of the gases is neither uniform nor the same as that of the fuel."

H_d = Heat units developed per 1 lb. fuel, less latent heat of any moisture evaporated from the fuel.

H_a = Heat units available above temperature of steam, $= H_d - w\,(T_s - 60)$.

A = lbs air per lb. fuel; assumed temperature 60° F.

s = specific heat of gases, taken as ·24.

w = heat capacity of gases, $= s\,(A + 1)$.

F = heating surface exposed to radiant heat from fuel or flame, in square feet per lb. fuel.

S = tube or flue surface, square feet per lb. fuel.

v = speed of gases in tubes or flues, feet per second.

T_g = temperature of gases, degrees Faht.

T_s = temperature of steam, degrees Faht.

B = coefficient of transmission, = 1250 when same is calculated step by step for successive intervals, terminating at the following values of S, respectively: ·05, ·15, ·3, ·5, ·8, 1·3, 2, 3, 4·5, 6·5, 9.

Then, heat-units absorbed in fire-box per 1 lb. fuel.

$$= H_a \times \left(1 - \frac{A}{A + 45\,F}\right) \quad . \quad . \quad . \quad . \quad (1)$$

Available heat-units remaining in gases leaving fire-box

$$= H_a \times \frac{A}{A + 45\,F} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Temperature of gases leaving fire-box

$$= \left(\frac{H_a}{w} \times \frac{A}{A + 45\,F}\right) + T_s \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$\text{Speed of gases} = v = \frac{A \times (T_g + 461)}{144{,}000\ C} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Units transmitted per square foot per degree per hour in tubes or flues

$$= \frac{T_g + T_s + 922}{2} \times \frac{\sqrt{v}}{B} \quad . \quad . \quad . \quad . \quad (5)$$

Some tables of results obtained by the use of these formulæ, and some diagrams of curves will be found in Chap. IX.

It will be interesting to compare with Mr. Hudson's estimates the following figures of the actual velocity of gases in boiler flues as given by Mr. J. T. Milton[1]: "Taking an ordinary return-tube boiler, burning 17 lbs. of coal per square foot of grate, and using 24 lbs. of air per pound of fuel, and assuming a temperature of 1664° and 887° at the ends of the tubes, temperatures given by Mr. Oram as having been verified in some experiments made at Devonport with this class of boiler, it will be found that the gases have a velocity of about 32 feet per second on entering the tubes, and of 20 feet per second on leaving them; their mean velocity will therefore be about 26 feet per second, and the time taken to traverse a tube 6 ft. 6 ins. long will be only $\frac{1}{4}$ second. The total time any portion of gas remains in the boiler is thus probably considerably less than a second. In a Belleville boiler of the type used in the 'Powerful,' assuming a consumption of 24 lbs. per square foot of grate, Mr. Oram gives the funnel temperature as 650°. Assuming the same proportion of air as before, and that the temperature of gases when entering the tubes is 1600°, the velocity at the entrance between the tubes will be about 32 feet, and at exit 17 feet per second; the time taken in traversing the tube spaces will be about $\frac{1}{4}$ second, and the total time in the boiler will be about $\frac{3}{4}$ second, which is not very different to the time the gases remain in the ordinary boiler."

With forced combustion and high rates of combustion these times are proportionately reduced.

Professor Rankine's Formula.—In connection with this subject reference is constantly made to Professor Rankine's formula (on

[1] Min. Proc. Inst. C.E. Vol. cxxxvii, p. 173. *See also* Chap. III, p. 66 (ante) velocity of gases.

p. 260 of "A Manual of the Steam Engine," etc., 1859) as if it were a final and ultimate expression of law on this subject. Nothing could be more mistaken than this idea.

Professor Rankine stated (at p. 257) that the rate of internal conduction through a given substance, expressed in thermal units per square foot of area per hour, is proportional

1. To the rate at which the temperature varies along a line perpendicular to the section through which the heat is passing, and
2. To the internal conductivity of the substance, which depends upon its nature.

When heat is passed across a metal plate from a fluid on one side to another at the opposite side, factors of external and internal thermal resistance are introduced, and when the total thermal resistance is thus provided for, Professor Rankine thus expressed the rate of conduction—

$$q = \frac{T' - T}{\sigma' + \sigma + \rho x}$$

"when T′ and T are now the temperatures not of the two surfaces of the plate, but of the two fluids which are respectively in contact with its two faces";

$\sigma' + \sigma$ being the coefficients of external resistance, and

ρ being the coefficient of internal resistance (estimated by Rankine at $\cdot 0096x$, when q is expressed in thermal units per hour per square foot of area and x in inches),

x being the thickness of the plate.

After giving from Péclet an expression for the value of $\sigma' + \sigma$, Professor Rankine proceeded to introduce his empirical formula as follows:—

"It will be shown in a subsequent article that the results of experiments on the evaporative power of boilers agree very well with the following approximate formula for the thermal resistance of boiler plates and tubes—

$$\sigma' + \sigma = \frac{a}{T' - T}$$

which gives for the rate of conduction per square foot of surface per hour—

$$q = \frac{(T' - T)^2}{a}$$

He added, "This formula is not proposed as being more than a rough approximation, but its simplicity makes it very convenient, and it will be shown that it is near enough to the truth for its purpose. The value of *a* lies between 160 and 200." The results of experiments referred to in this extract are given on pages 295 to 298 of "The Steam Engine" (same edition), and they are of far too crude a nature to serve as the foundation of anything but "a rough approximation."

The following remarks by Professor R. H. Smith show also the wide divergence between Rankine's empirical formula and Péclet's rule :—

"From Péclet's experiments, the rate of conduction in English heat units per hour per square foot may be called q, and appears to be

$$q = 1{\cdot}78\left\{1 + {\cdot}0037\ (t - t_b)\right\}(t - t_b)$$

where t is the surface gas temperature, and t_b that of the water in the boiler. A few examples of the results of this formula are given in the annexed Table—

TABLE XLVIII.

$t-t_b$.	q	$\frac{(t-t_b)^2}{120}$
100	244	83
200	620	333
500	2,540	2,083
1,000	8,380	8,333
1,500	17,520	18,750
2,000	29,960	33,333

"The third column gives, for the sake of comparison, the results of a formula of the form suggested and used by Rankine. Rankine, however, gives the divisor to be used in this latter as lying between 160 and 200. With this it would never agree with Péclet's results, except for such high temperatures as do not occur in boilers, even in the fire-boxes. With the divisor 120 it is seen to agree for a temperature difference of about

1000°, to give too small figures for low temperatures, and about 10 per cent. too high for about 2000° temperature difference."

Professor Witz's Experiments.—It remains for us to notice some experiments carried out by Professor Aimèe Witz (and recorded in the "Comptes Rendus de l'Academie des Sciences," Paris, Vol. cxiv., 1892, p. 411[1]), on account of the light which they throw upon the effect of increasing the temperature of the metal plates in contact with water, and also because of the remarkable rate of evaporation reached in one or two instances. The first series of experiments showed the time required to evaporate 40 grammes (1·41 oz.) of water at different temperatures of plate—

TABLE XLIX.

		Time required.
At 141° Cent. or 286° Fahr....	... ...	2 min. 0 sec.
„ 194 „ „ 381 „	... ...	0 „ 38 „
„ 243 „ „ 470 „	... ...	0 „ 25 „
„ 260 „ „ 500 „	... ...	0 „ 22 „
„ 320 „ „ 608 „	... ...	0 „ 20 „
„ cherry red...	... ...	10 „ 20 „

In the last instance the spheroidal condition of the water was realised, and the rate of evaporation became at once 31 times less than that at 320° C. In order to prove whether the spheroidal condition was likely to be realised easily with a larger quantity of water in a boiler, a series of experiments was then made with a small vertical cylindrical boiler 3·017 decimetres (practically 12 inches) diameter, so constructed that various thicknesses of bottom plate from 1 to 12 millimetres could be used. The water was maintained at a constant level, the quantity evaporated in given time being measured, but the temperature of the plate was not measured, as the result inquired into was that of the possible rate of evaporation with excessive heating, and the possibility of the spheroidal condition occurring. The following Table gives results with a height of 3·15 inches of water.

[1] For abstract see Min. Proc. Inst. C.E. Vol. cviii., p. 473.

TABLE L.

Nature of Heating.	Barometric Pressure.	Temperature of Feed Water.		Water evaporated per hour.	
		Centigrade degrees.	Faht. degrees.	Kilog. per Sq. Metre.	Lbs. per sq. foot.
Seven Bunsen Burners ...	29·33	15	59	63·3	13·0
Seven Bunsen Burners and one air blast ...	29·84	16	61	179·4	36·8
Seven Bunsen Burners and one oxy-hydrogen blow pipe ...	29·84	18	65	200·9	41·2
Seven Bunsen Burners and three blow pipes...	29·65	19	67	263·2	54·0
Coke with air blast ...	29·92	19	67	433·5	88·9
Seven Bunsen Burners, one air blast, and one oxy-hydrogen blow pipe	29·70	14	57	662·8	136
Coke with air blast ...	29·92	90	194	994·3	204

In the case of the last two experiments the water was first all evaporated away, and the plate, which was 12 millimetres, or practically ½ inch thick, was allowed to become red hot, when the feed water was again admitted, and the level maintained as before. In none of the first five experiments did the plate become red hot, the surface of the plate in contact with the water having been carefully cleansed. The supports of the boiler were, however, raised to a dark red heat, and the water was violently agitated. In the last two cases the plate remained red hot, without perceptible cooling in the last case, and the boiling was very violent. Although Professor Witz concluded that the water in a boiler need not necessarily assume the spheroidal state, even if the plates became red hot, yet the danger of explosion would be none the less present, on account of the inability of the metal to resist the strain of steam pressure at that temperature.

The second last result shows a similar rate of evaporation to that which was attained in Mr. C. R. Lang's experiments, and we are thus shown that a definite rate of heat transmission may take place with widely different static conditions of temperature in the metal plate.

It is to be regretted that more extended information regarding these experiments of Professor Witz was not published, as much might be learned from them if all the conditions were made known. We may, however, conclude, from all the evidence which has been before us, that each square foot of heating surface in a boiler properly constructed and worked should be good for the evaporation of from 80 to 100 lbs. of water per hour. Theoretically, considering the question of conduction through the metal alone, the heat requisite for a much larger result should be readily transmitted, but making allowance for resistance, and presuming that Professor Perry's hopeful anticipation (noted on p. 200, *ante*) is not at once realised, an increase from the presently accepted 10 lbs. per square foot per hour to anything approaching the figures given above, is very much wanted.

Reference may also be made to the Paper on the Efficiency of Steam Boilers and Surface Condensers read by T. E. Stanton to the Owens College Engineering Society, and published in the *Mechanical Engineer*, 31 March, 1900, Vol. v., pp. 445–448; and to the Theoretical Consideration of Evaporation in Boilers by H. Brillié, in *Le Génie Civil*, August and September, 1897, pp. 260 *et seq.* (see Abs. in Min. Proc. Inst. C. E., Vol. cxxxi., p. 480.)

CHAPTER V.

CIRCULATION OF WATER.

IT is in connection with the transmission of the heat in boilers that the circulation of the water possesses its chief importance. Were water a good conductor of heat, like mercury, motion would not be to the same extent necessary, even though the heat vibrations had to adapt themselves to a liquid form of matter in passing to it from a solid. Freedom of escape for the vapour from the liquid would be the principal condition needing a proper provision, and under such circumstances the greatest heat would be applied to the liquid near the surface, and a less temperature as the distance from that part increased. Water being a bad conductor of heat, it is only by means of convection currents that the total quantity of water contained in a boiler can readily be heated up to and maintained at or near the temperature of steam formation. The direction of movement of these convection currents is an upward one, in accordance with the laws of gravity, the heated portions of water being rendered specifically lighter by their expansion. Hence in most boilers the fire is placed, or the heat of the fire is applied, at as low a point as possible, and no attempt is made to heat the water from above downwards. In this way the movement of the heated particles of water assists, and in turn is assisted by, that of the steam, and when the tubes or water passages are of small area individually, in result the water is carried along at a considerable speed. Water-tube boilers, in general, present conditions which produce a rapidity of such movement of the water much beyond what could be known in tank or drum boilers, and it is no doubt in great part to this that their comparatively rapid steaming power is due. Yet further examination shows that movement of that kind is perhaps not an unmixed blessing, because large quantities of water which cannot be at the full temperature of the steam are carried along with the currents and thrown forcibly into the steam space in the closest contact with the steam. Before they can be separated from the steam and returned to the water space

by down-comers, there is no doubt that they must exert a sensible cooling effect on the steam, and probably they thus cause the work of steam formation to some extent to be done over again by a further expenditure of heat. Certainly if the steam could at once escape from the hottest portion of the water into the steam space without the necessity for its mingling with any water of a less temperature, some useless expenditure of heat would be prevented, and we should be a step nearer the realisation of the best result. We have seen in Chapter IV. that rapid movement of the water is absolutely essential to heat transmission, and therefore the problem that lies before us is that of how to produce the maximum useful rate of movement of the water over the heating surface whilst the minimum quantity is allowed to mingle with the steam. In any solution of this problem we have also to provide for the passage of the currents of water and hot gases in opposite directions, as it is quite clear that this arrangement is demanded as one of the conditions of successful heat transmission.

The circulation of water in boilers has usually been considered, mainly, if not wholly, in view of the prevention of over-heating portions of the boiler surfaces, and investigations of the action have hitherto been concerned almost entirely with the quantity of water put in motion in individual boilers, and with the mode in which this movement has been produced in them. Consequently in almost all treatises on boilers the circulation of the water has been dealt with as if it were a sort of independent action regulating the work done by, and the life of, boilers, and therefore requiring provision for its being unhindered, but only so that rapid steaming should proceed without damage to the boiler, and not in strict relation to the requirements of heat transmission.

The truth, however, is, that water circulation is one of the things connected with the action of boilers which itself requires to be governed and directed, in order that the highest degree of efficiency in steam raising may be reached, and in this view the *velocity* of the movement of the water requires to be considered.

Two Kinds of Circulation.—There are evidently two kinds of circulation possible :—

1. That which is due to the natural action of boiling. In this case the water, when once steam is formed, is constantly

thrown upwards and returns by gravity to the lowest level, either with regular movement, when channels are provided for this return, or spasmodically, when steam formation is allowed to interfere with it.

2. That which is forced or produced by mechanical means, in which case both quantity, speed and direction can be wholly under control.

Natural Circulation by Boiling.—Regarding natural circulation, as produced by the process of boiling or steam production, numerous theories have been advanced to explain certain phenomena which have been noticed with particular boilers, but, as in other matters, experimenters have forgotten the many ways in which the conditions under which their results were obtained might be altered, and have too hastily formulated "rules" or "laws," for general application, on the evidence of experiments too few in number and too limited in their conditions.

Clerk Maxwell on "Boiling."—No explanation of the phenomena of boiling could be more simple or complete than that of Professor Clerk Maxwell (in "Theory of Heat," p. 23), which is as follows: "When water is heated in the ordinary way, by applying heat to the bottom of a vessel, the lowest layer of the water becomes hot first, and by its expansion it becomes lighter than the colder water above and gradually rises, so that a gentle circulation of water is kept up and the whole water is gradually warmed, though the lowest layer is always the hottest. As the temperature increases, the absorbed air, which is generally found in ordinary water, is expelled and rises in small bubbles without noise. At last the water in contact with the heated metal becomes so hot that, in spite of the pressure of the atmosphere on the surface of the water, the additional pressure due to the water in the vessel, and the cohesion of the water itself, some of the water at the bottom is transformed into steam, forming a bubble adhering to the bottom of the vessel. As soon as a bubble is formed evaporation goes on rapidly from the water all round it, so that it soon grows large and rises from the bottom. If the upper part of the water into which the bubble rises is still below the boiling temperature, the bubble is condensed, and its sides come together with a sharp rattling noise, called simmering. But the rise of the bubbles stirs the water about much more vigorously than the mere expansion of the

water, so that the water is soon heated throughout and brought to the boil, and then the bubbles enlarge rapidly during their whole ascent, and burst into the air, throwing the water about and making the well-known softer and more rolling noise of boiling." Although this description concerns itself primarily with the operation of boiling in an open vessel, yet it applies equally well to boiling in the same vessel when closed and under pressure, as practically nothing is then altered but the comparative volume of the bubbles of steam. There are two points mentioned in the description which are frequently overlooked by other observers, and these are—(1) that the water in contact with the heating surface is necessarily hotter than the rest of the water in circulation, and (2) that the bubbles of steam enlarge as they ascend in consequence of the heat of the steam causing evaporation from the surrounding water, as soon as the water has reached such a temperature that no condensation of the bubbles takes place during their ascent. This important part, which is played by the heat of the steam in the bubbles is constantly overlooked. It is necessarily absent in the case of bubbles of air blown through the water in experiments (although such bubbles may enlarge slightly on account of diminution of pressure), and in that of glass bubbles and corks, which are also used to illustrate the action of bubbles of steam, and consequently reasoning which is founded on phenomena produced with such apparatus must be to some extent unsound.

Clerk Maxwell on "Convection Currents."—More particularly with reference to the diffusion of heat in fluids, Professor Clerk Maxwell has said (*op. cit.* p. 230), "When the application of heat to a fluid causes it to expand or to contract, it is thereby rendered rarer or denser than the neighbouring parts of the fluid; and if the fluid is at the same time acted on by gravity, it tends to form an upward or downward current of the heated fluid, which is, of course, accompanied by a current of the more remote parts of the fluid in the opposite direction.

"The fluid is thus made to circulate, fresh portions of fluid are brought into the neighbourhood of the source of heat, and these when heated travel, carrying their heat with them into other regions. Such currents, caused by the application of heat and carrying this heat with them, are called convection currents. They play a most important part in natural phenomena, by

causing a much more rapid diffusion of heat than would take place by conduction alone in the same medium, if restrained from moving. The actual diffusion of heat from one part of the fluid to another takes place, of course, by conduction ; but on account of the motion of the fluid, the isothermal surfaces are so extended, and in some cases contorted, that their areas are greatly increased, while the distances between them are diminished, so that true conduction goes on much more rapidly than if the medium were at rest."

Although it is true, as Professor Clerk Maxwell has said, that convection currents depend on changes of density in a fluid acted upon by gravity, and that, were gravity absent, there would be no convection currents, yet this does not prove, as Mr. Thornycroft[1] contended, that "the force of gravity is the real force and the only force we have to depend on for the circulation of water in the boiler." He continues, "If we could go to another planet, where the force of gravity was larger, we might have less trouble with the circulation in our boilers. On the other hand if we could take the boiler down to the centre of the earth, where gravity may be supposed to be *nil*, or acting equally in all directions, then no construction of boiler that we could adopt would enable us to make one that would work. It would be sure to burn."

Under such circumstances, however, other conditions, such as those of combustion, would also be altered and if no movement of air could be obtained (as would also be the case), how would the fire—not to speak of the boiler—burn ? In addition to that, it is always possible to rely upon mechanical force to cause circulation of the water ; and in any case, it is under present well-known mundane conditions that we have to consider the efficient working of boilers.

A considerable variety of forms of apparatus has been used in experiments made to illustrate, or to demonstrate, certain ideas connected with this subject, but the conclusions drawn from these experiments have not always been consistent or sufficiently conclusive.

Matthey's Experiments—Action of Bubbles.—Two experiments (which were excellent specimens of a class of such) were

[1] Trans. Inst. N. A., Vol. xxxvii., pp. 135, 136.

shown by Mr. C. A. Matthey[1] to the Inst. of Engineers and Shipbuilders in Scotland for the purpose of throwing light upon the question whether the presence of a bubble of gas, or of a solid body lighter than water, immersed in a column of water and rising through it, diminished, or did not diminish, the hydrostatic pressure at the bottom of the column. A vertical glass tube, 2 inches in diameter and 5 feet high, connected at the bottom with another glass tube of the same height, but only one eighth of an inch in diameter, was placed vertically upon an electro-magnet D, as shown in Fig. 98. The tubes were nearly filled with water, and a glass bubble C, a little smaller than the large tube, floated within it with the water level at B B. To the bottom of the glass bubble was attached a small piece of soft iron which, when the bubble was pushed down to the bottom of the tube, caused it to be anchored there by the attractive force of the electro-magnet. When the bubble was fully immersed and prevented from rising, the water level rose, by virtue of its displacement, to the level A A, the pressure on the bottom being registered by the level of the water in the small gauge tube. On breaking the electric circuit through the magnet D the bubble was released and free to rise in the tube.[2] As soon as it moved the water level began to fall from A towards B, in both tubes, and it dropped to B as soon as the bubble had attained its maximum velocity of ascent. "This showed," Mr. Matthey remarked, "that the pressure of a free bubble in the large tube made the pressure on its bottom less than that which corresponded to the height of the water in it." It may be, however, that the apparent diminishing of the hydrostatic head was an effect due to setting the water in motion, as it is undoubted that a complex system of stream lines must accompany the movement of the bubble through the water.

In another experiment shown with a **U**-tube, Fig. 99, the water level stood at E E, and a nozzle and pipe were provided at F, by means of which gas or air could be blown into the left-hand limb of the **U**. On blowing gas into the left-hand limb by this nozzle, the water level was raised by the

[1] Trans. Inst. Eng. and Shipbuilders in Scotland, Vol. xli., pp. 147–150.

[2] This is a better mode of procedure than has been usual in such experiments. See Trans. Inst. Marine Engineers, Vol. x., No. lxxvii., page 24; *Engineering*, Vol. lx., p. 430, Vol. lxi., p. 436.

bubbles to G or G_1, but the level in the right-hand limb remained at E ; and this was so, whether much or little gas was forced into the tube. Mr. Matthey held that this demonstrated that the pressure at the bottom of the **U**-tube was the same as if the gas were absent, and he added, "This disposed of the distinction

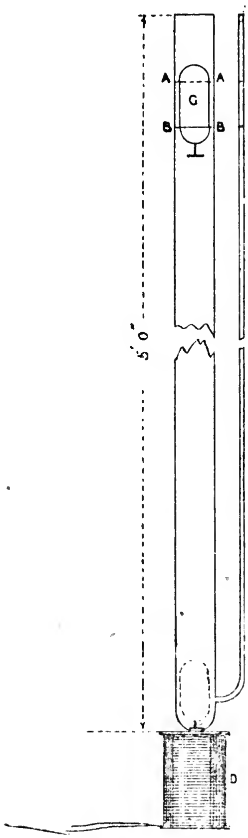


FIG. 98.

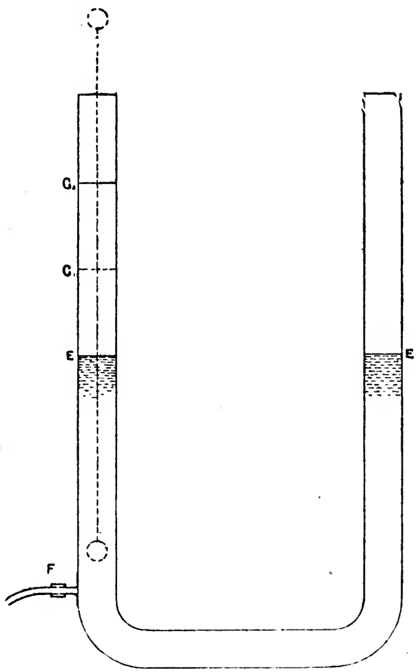


FIG. 99.

which had been drawn between the case where there was continuity of water round the bubbles, and where the bubbles made plugs of gas and water alternately, completely occupying the section of the tube. It was sometimes said that the water was entrained by the bubbles ; or that the bubbles rose in virtue of

their lightness and dragged the water with them. Such expressions were loose and unscientific.[1] The bubbles which rose in the left-hand leg in Fig. 99 did not drag any water out of the other leg. But, if instead of the bubbles, a solid ball attached to a fine wire was placed at the bottom of the left-hand leg, and drawn upwards by means of the wire, the level in the right-hand leg became depressed, while in the left-hand leg it rose. This might be called entrainment, but it was produced by an external force, not by the mutual action of the water and the immersed body."

This experiment with the bubbles shows that the force which impels the advance and ascent of the bubbles of gas in one limb of the tube evidently *re-acts* to prevent any alteration of the head of water in the other limb, and it is probable that the same result attends the formation and ascent of steam bubbles in the same apparatus. This is a different action from that supposed by Mr. Thornycroft,[2] in which periodical *accumulation* of steam takes place in the tube and by its expansion propels the water out of the upper end, whilst it simultaneously pushes back the water at the lower end and drives some of the water out of the tube in that direction.

If, however, the two limbs of the **U**-tube be joined by a horizontal tube just above E, the water which is forced up to G will then run across by the horizontal connection to the right hand limb, down which it will flow, and, thus altering the hydrostatic head at that point, will produce a movement or circulation of the water in the **U**-tube. It is evident that it is in this latter form that we approach the conditions which ought to be present in boilers, as they must provide not only for the free escape of the steam from the water, but also for the due return of the water which is carried along by the steam.

Cause of Movement of Water.—As to the cause of movement in such tubes, there is a variety of opinions. Thus in one volume[3] we read, "If the water is as shown in Fig. 100 and the bubbles of steam rising in it as shown, the bubbles may be rising very rapidly and producing no circulation, for the head of the

[1] See also remarks by Mr. C. H. Wingfield in Trans. Inst. Naval Architects, Vol. xxxvii., pp. 287, 288.

[2] Min. Proc. Inst. C. E., Vol. xcix., p. 46.

[3] "Steam Boilers," by George Halliday. London, 1897, p. 279.

water will still be the same as in the other limb. . . . These bubbles might be replaced by corks, and every one knows that a cork rising to the surface will not produce circulation." But at page 293 of the same volume we have some account of experiments made by Professor Watkinson in these words: "The first kind of circulation, viz., that produced by water following the rising of the steam bubbles through the water, is illustrated in Fig. 101. There the steam bubbles do not fill the base of the left tube, nor is there any foam to completely fill any part of the tube, and the movement of the water is, when all at the same temperature, produced entirely by the entraining action of the bubbles of steam. A further proof of this is shown in Fig. 102, where a tube is inserted inside of another, and a bent blow-pipe is led down as shown. When air is blown down through the tube, it rises in bubbles from the nozzle at C, producing an upward movement of the water by the entraining action of the bubbles. . . . The circulation is, then, not produced in any way by a difference in density between the two vertical limbs. And if further proof be needed, it is supplied by the third experiment, Fig. 103, where the movement of a number of beads, threaded on a wire upwards or downwards, makes the water in the tubes follow the beads upwards or downwards in the same way as it follows the bubbles of steam upwards in limb A, Fig. 101."

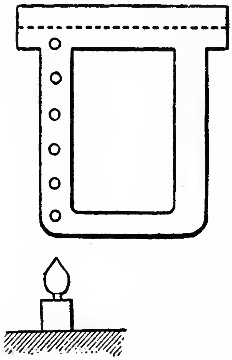


FIG. 100.

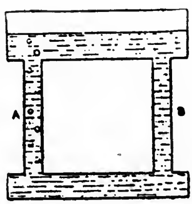


FIG. 101.

Here, then, we have two diametrically opposite opinions given by two authorities on the same point or question. It says much for the candour of the author of one of them that we find both expressions of opinion almost side by side in the same volume. It is evident, however, that we must refer Fig. 103 back to Mr. Matthey's experiment on p. 223, and to the difference shown by him between bubbles of gas and a solid ball on a fine wire in Fig. 99. There is no fair comparison possible

between a solid piston or diaphragm, of whatever size or shape, moved by external force in a liquid, and the movement of free bubbles of air, gas or steam, in the same mass of liquid. As to the other matter, there is undoubtedly some movement of the water produced by the passage of the bubbles of air or gas, and, as we have already seen, much more disturbance of the liquid produced by the movement of bubbles of steam which we found in it, but whether, under the circumstances supposed, that movement is sufficient to provide efficient circulation in a boiler, does not concern us, because the conditions are not those of the rapid generation of steam, and intermediate stages must quickly pass till this one is reached. It is certain, however, that without the additional movement of the water, due to alteration of head in the down-comer, the movement of the bubbles alone could not cause any general circulation of the water in a boiler.

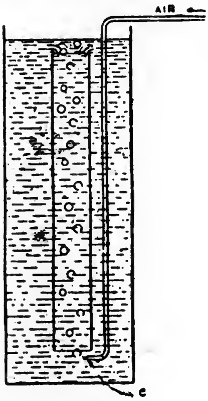


FIG. 102.

Additional light is thrown on this subject by the paper, "On the Ascent of Hollow Glass Bulbs in Liquids," read by Professor E. J. Mills, D.Sc., F.R.S., to the Physical Society of London, on May 14, 1881, and published in the *Phil. Mag.* in July of that year. Dr. Mills showed the effect of variation of the diameter of the tube on the speed of ascent ; also the effect of change in the amount of unbalanced pressure, to which ascent is due ; and also the effects of having gases of different specific gravity in the bulbs, and gave an algebraic expression of the law under which in each case the ascent took place.

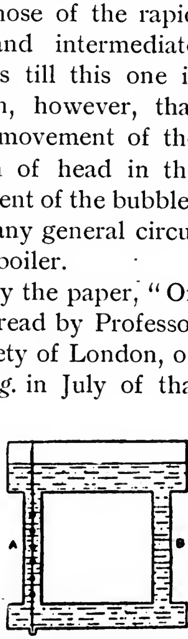


FIG. 103.

Action of Rapid Formation of Steam.—When steam is being rapidly formed, all are agreed that with small tubes or passages the steam bubbles form plugs or pistons which practically force the water before them, and in effect in many boilers produce fairly continuous fountains or cascades from almost all the tubes into the upper chamber of the boiler. It is

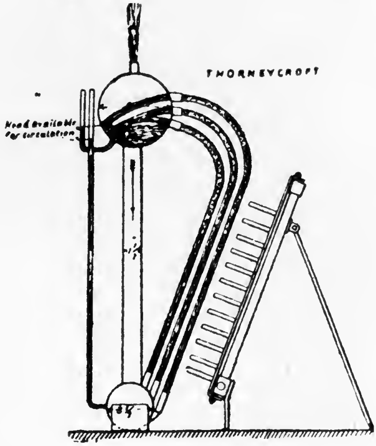
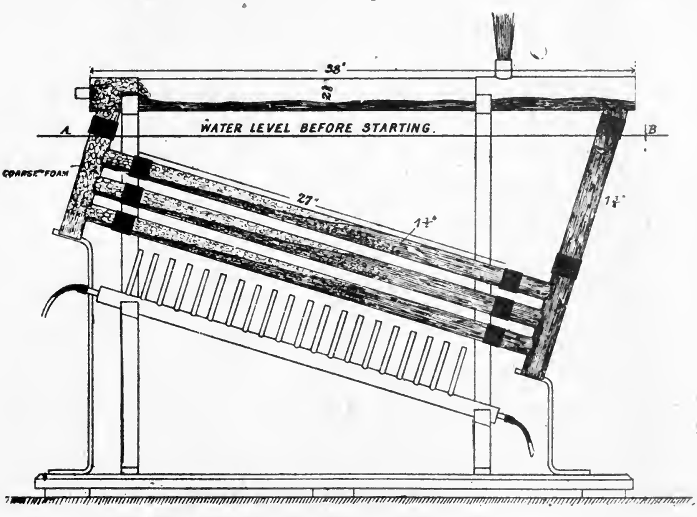


FIG. 104.

quite clear that gravity is not the only force concerned in *this* result, but the quantity of water so thrown up, to some extent contrary to the action of gravity, contributes by its descent to an increased gravity result, and otherwise assists in the healthy action of the boiler. Fig. 104 illustrates this phenomenon in a boiler of the Thornycroft pattern, with water-tubes delivering above the water level of the boiler.

With larger tubes, and with tubes nearly horizontal, it stands to reason that these plugs or pistons can rarely, if at all, be formed, and in such case the circulation will be neither so rapid nor so regular. That is to



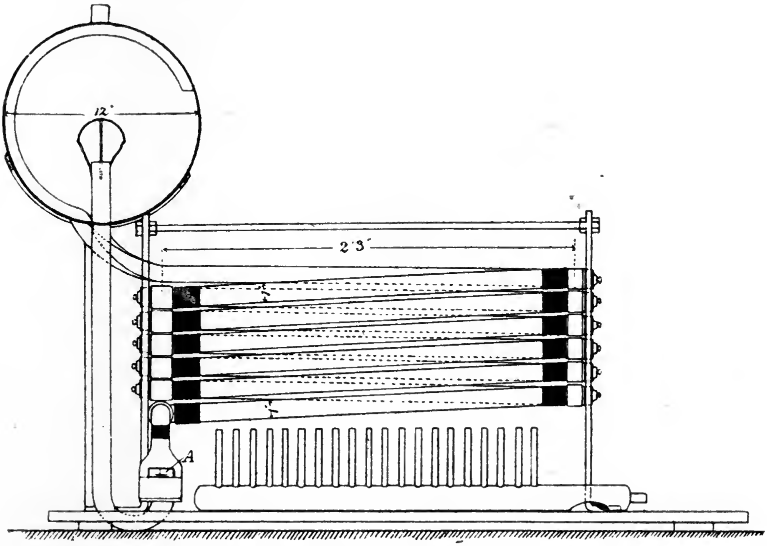
MODEL OF BABCOCK AND WILLCOX BOILER

FIG. 105.

say, the quantity of water forced into movement by the action of the steam cannot be so large. In some cases foam is formed, but he existence of foam in tubes and headers is most undesirable

from the point of view of heat transmission, though it is not so bad as the presence of a large quantity of steam which can escape only slowly, whilst it prevents the entry of sufficient water into the tube. Yet both of these conditions are likely to exist in boilers of the inclined tube, and Belleville classes with large tubes.

Fig. 105 shows one of these conditions in an inclined tube boiler, as existing in a model in action. The foam appears in the header and at the top ends of the tubes. The model of a Belleville boiler exhibited in action by Professor Watkinson[1] during



MODEL OF BELLEVILLE BOILER.

FIG. 106.

a discussion on water-tube boilers at the Institution of Engineers and Shipbuilders in Scotland, showed a considerable quantity of water forced into, and retained in the steam drum (above the normal water-line of the boiler), and some of the inclined tubes near the top kept almost full of steam, in consequence of the water which had been forced up into the drum being unable to re-enter the tubes by the steam passage. This model is shown in Fig. 106. In discussing the subject, as illustrated by the glass

[1] See Trans. Inst. Eng. and Shipbuilders in Scotland, Vol. xli., pp. 249-255.

models on the occasion referred to, it was remarked[1] that "taking the indications given by the action of Professor Watkinson's glass models, the Belleville boiler ought to have, on Professor Watkinson's basis of reasoning, the best circulation, because it showed the largest quantity of water forced up the greatest distance into the drum above the water level. But it really showed the worst circulation, because that water (the position of which really constituted Professor Watkinson's gauge of the amount of circulation) was maintained there at the expense of the upper rows of tubes, which were kept nearly empty of water, and thus exposed to over-heating and to easy distortion by strains, such as those caused by the pitching and rolling of steam vessels." The observations recorded in Chap. II., pp. 45–48 show that there is some foundation for the opinion that such action really takes place in this boiler.

Where plugs or pistons of steam are not formed, there is a continuous stream of bubbles rushing upwards, always accompanied by more or less water, which is, as Clerk Maxwell remarked, thrown up into the steam space.

Down-comers.—It is no doubt the proper course in boiler design to provide distinct channels or passages which are to be used as down-comers only, where the circulation is that produced by boiling, so that the water carried up may descend continuously without any interruption from the formation of steam in the down-comer passages.[2] This is sufficiently apparent to be axiomatic, as is also the principle that in water-tube boilers the more nearly vertical the water passages (for both up and down currents) are, the more truly are they arranged in harmony with the laws of the circulation of heated fluids. These principles the author advocated and defended in a series of letters to *Engineering*[3] in 1877, and in spite of the popularity of some boilers constructed of water-tubes only slightly inclined from the horizontal, it is certain that the best results can never be reached by any compromise with fundamental principles. The experiments described by Mr. John Watt to the Institution of Naval

[1] See Trans. Inst. Eng. and Shipbuilders in Scotland, Vol. xli., p. 127.

[2] See Trans. Inst. N. A., Vol. xxxvii., p. 287, 288.

[3] See *Engineering*, 13th and 20th April, 4th, 11th, and 18th May, 1st June and 20th July, 1877, also "On the Design and Use of Boilers," *Engineering*, Vol. xxvi., 164.

Architects[1] in March, 1896, are as inconclusive on this point as are the first two bold assertions which he called "rules" or "laws" in his paper of March, 1874, from which he quoted them with approval for the instruction of the Institution of Naval Architects. If it is ridiculous to expect a good result from a Cornish boiler placed on end, as Mr. Watt once contended,[2] how much more so to expect a Root boiler or a Babcock and Wilcox boiler to work at all when placed with the water-tubes in a vertical position. They would then possess no proper means of being either heated or supplied with water, and no competent person could compare them, under such circumstances, with any water-tube boiler properly constructed with vertical water-tubes. The defects in Mr. Watt's reasoning from his experiments were demonstrated by Mr. Thornycroft and Mr. Blechynden in Trans. Inst. N. A., Vol. xxxvii., pp. 182-284, and by Mr. Normand's paper "On Water-Tube Boilers" in the same volume, p. 109.

Regarding the use of separate down-comers, it seems to be held by some makers that boilers composed of nearly vertical water-tubes which deliver steam below water level, under the ordinary method and conditions of firing, are sure to have some of the tubes kept exposed to a very much higher temperature than others which are farther from the fire, and that the water will descend by these cooler tubes, even when no regular down-comer is provided, in spite of the fact that these tubes are exposed to some heating. Mr. W. M. McFarland records[3] that some years ago Mr. C. Ward, in America, announced that he did not find external down-comer tubes to be necessary. "As a matter of necessity," he said, "some tubes will be cooler than others, and if the water goes up in some, it must come down in others." There appears to be, however, rather too much haphazard in this plan, which practically allows the boiler to choose for itself which are to be its down-comer passages ; and it is quite conceivable that such a change of conditions might arise in the course of working as would upset the ordinary sequence of the actions depended upon, and interfere with the safety of the boiler, or, in any case, seriously diminish its

[1] Trans. I. N. A., Vol. xxxvii., p. 261.

[2] See *Engineering*, May 25, 1877.

[3] Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xli., p. 138.

efficiency. With ordinary arrangements for firing, and with natural circulation of the water due to the action of boiling, a boiler might continue to work steadily for some time, under such conditions as Mr. Ward indicated, but a stress of circumstances might arise at any moment which would destroy the equilibrium of the apparatus, so that Mr. Ward's plan could not be reckoned upon as a very satisfactory one. A little more heat than usual getting to the tubes acting as down-comers might interrupt the current of water by the formation of steam in them, and might thus force the water to remain in the upper portions of the boiler till some damage was done by the overheating of tubes.

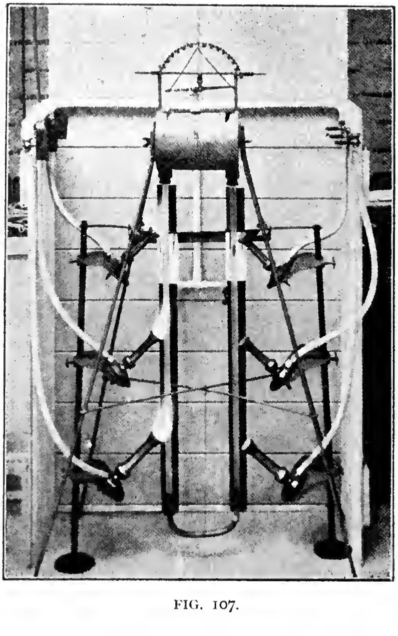


FIG. 107.

Mr. Yarrow's Experiments on Down-comers.—Mr. A. F. Yarrow, however, carried out some very interesting experiments which show that it may be possible to heat the down-comers of a boiler without interfering with the direction of the current of water. These experiments are shown in the following illustrations and described in Mr. Yarrow's words. "Fig 107 represents a glass **U**- tube, the upper extremities being fixed to a chamber containing water. At the top will be seen a balance, at one end of which is a thin cord with a bob attached, this bob being immersed in one of the columns. Any circulation of water, by acting on the bob, would be indicated by the balance. It will be seen that there are three lamps on each side, adapted for heating the two tubes. In Fig. 107 the three lamps on one side are alight and circulation in this tube is naturally set up in an upward direction drawing the water down the tube on the opposite side.

"After this circulation was started the three lamps heating the

other tube, see Fig. 108 (that is, the one in which the water was moving downwards), were lighted, and it was found, contrary to general opinion, that the circulation was not stopped or retarded, but actually accelerated, as will be seen by the position of the balance in Fig. 108. "Some further trials were made with a similar apparatus, but on a larger scale, under pressures varying from 50 to 150 lbs. per square inch, and it was found that when once circulation was set up in a certain direction, all the heat might be applied to the down current without reversing the circulation, which thus remained constant. This was a result quite unexpected. It was thus proved that when once circulation is set up, it has a very strong tendency to remain constant."

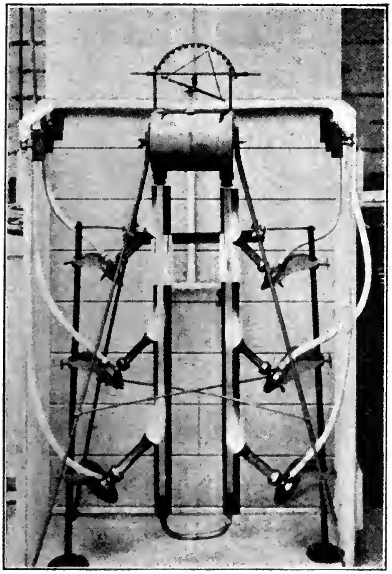


FIG. 108.

Mr. Yarrow's conclusion from these experiments is scarcely sufficient basis for proof of the larger question involved. The general conclusion, that the direction of circulation or movement of water when once set up tends to remain constant, is, no doubt, correct, because in order to alter the direction more force has to be brought to bear on the water than is required to set up the movement in the first instance. The already established movement has to be stopped and reversed. The same result is seen in the experiments with air bubbles, described by M. de Chasseloup-Laubat[1] and others, where the action of heat does not enter into the question. But the conclusion that when once circulation is set up in a certain direction *all* the heat may

[1] See Les Chaudières Marines par M. de Chasseloup Laubat, in Mem. de la Soc. des Ingenieurs Civils de France, April, 1897. See also Trans. Inst. Engineers and Shipbuilders, Vol. xli., p. 253.

be applied to the down-comer without reversing the direction, cannot with safety be applied to boilers in actual operation. The reason is apparent. In the case of tubes or models heated by gas flames, both the amount of heat and the part of the surface to which it is applied suffer no fluctuation, and moreover the amount of heat is not great and it is completely under control from moment to moment. The conditions are entirely different in the case of boilers with coal fires, operated either by natural or forced draught. The temperature is constantly varying from a far more fierce heat than that of Bunsen flames to a low degree, and the eddying of the currents of gases causes unequal and varying distribution of the heat. Moreover, the opening of furnace doors alone is sufficient to cause a radical alteration of the conditions. In such a case it would be far from prudent to trust to the continued or regular action of such down-comers, which could at almost any moment be thrown entirely out of gear. In reasoning from the results of experiments it is necessary always to give due consideration to the altered conditions of actual work, but this is frequently forgotten. Where, however, a boiler is composed of several rows of small tubes it is probable that the three or four rows nearest to the fire will screen off the heat from the outer rows, shading them from the radiation and interposing their large amount of surface to cool down the hot gases before these reach the outside rows. It is in just such a boiler as that of Mr. Yarrow that such a result is most likely to be experienced and his latest experiments [1] show how he has taken advantage of it and has even advanced a step, so that by admitting the feed water to these tubes he constitutes them a feed-heater for the supply of the boiler.

Chasseloup-Laubat's Summary.—A very useful summary of elementary experiments on circulation of water in boilers is given by M. de Chasseloup-Laubat in his excellent treatise on Les Chaudières Marines [2] (pages 76-94).

Bellens' Experiments.—Amongst the most interesting are some with models prepared by M. C. Bellens and described in his work on steam boilers.[3] M. Bellens prepared two models with

[1] Trans. Inst. N. A., Vol. xl. (March 31st, 1898.)

[2] Published in Memoires de la Société des Ingenieurs Civils de France. April, 1897.

[3] Traité des Chaudières à Vapeur, par Charles Bellens. Paris, 1895.

tubes respectively of 25 millimetres and 60 millimetres diameter, slightly inclined from the horizontal. These are shown in Figs. 109 and 110.

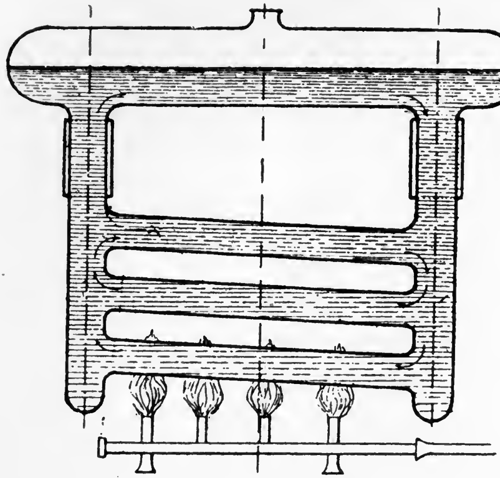


FIG. 109.

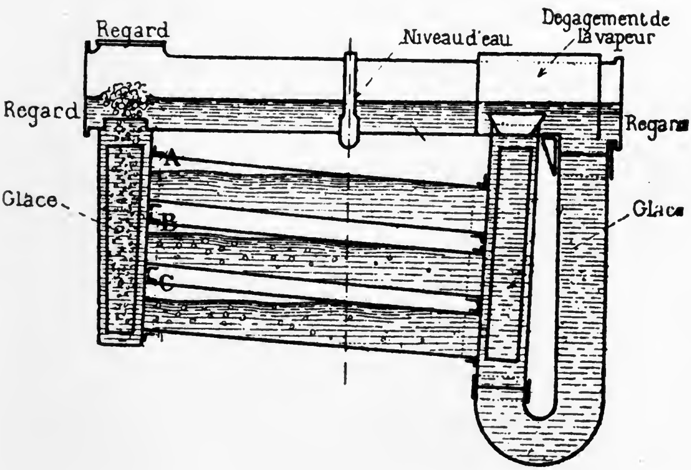


FIG. 110.

In the first (Fig. 109) the water was free to circulate in either direction, and the arrows show the course which it usually took.

In the second model (Fig. 110) means were introduced by which either the upper or lower extremity of the inclined tubes could be closed at will. M. Chasseloup-Laubat testifies that in these forms the circulation was very middling—as M. Bellens had also remarked in his interesting volume—and that a considerable part of the water set in motion by the steam bubbles returned by the upper, instead of, as ought to have been the case, by the lower end of the tubes. Moreover, the movement of the water in the second and third tubes from the bottom was extremely irregular. Not only was it fast or slow without apparent reason, but also it changed in direction, and sometimes the tubes were almost entirely filled with steam. These disturbances were produced chiefly at the moment when any variation of the heating took place. At A, B, and C (Fig. 110) a considerable space along the upper sides of the tubes is shown with steam only in contact with the tube surfaces. This is commonly seen in models having inclined tubes, and reveals the possibility of overheating which is often found in boilers constructed on that plan.

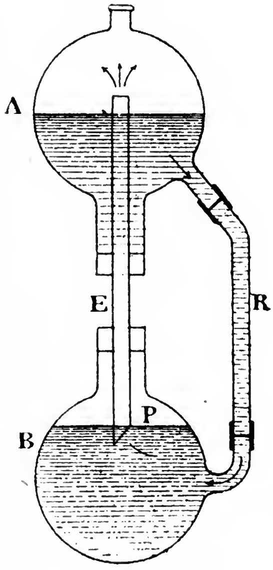


FIG. 111.

"*Émulseur*" *Tubes.*—Fig. 111 shows an apparatus, also constructed by M. Bellens, to illustrate the action of the "émulseurs" introduced by M. Dubiau for the purpose of producing a more active and forcible circulation of the water than that which is due only to the action of gravity. Two globes, A and B, are joined by a tube R, and by another tube E, of which latter the lower end is bevelled. The tube E is called the "émulseur" tube. On commencing to work, the lower globe B is completely filled with water, and then heat is applied to it. The steam accumulates in the upper portion of B, depressing the water level until the edge of the bevel P is reached. The steam then escapes by the tube E, and in doing so forces water up into the globe A. From that moment an

extremely active circulation is set up. The level of the steam remains constant unless the rate of heating is such that more steam is formed than can escape by the tube E. In this latter case we are not told what would happen, but may readily imagine what the result would be; and it is thus apparent that the safety of such apparatus depends entirely upon having a sufficient area of "émulseur" tubes to provide for variations in the rate of steam-raising.

Thornycroft's Experiment.—Mr. J. I. Thornycroft, in two papers presented to the Institution of Naval Architects,[1] described some interesting experiments made by him with a view to establish the superiority of boilers having water-tubes delivering their steam above the normal water level of the boiler, over those boilers whose tubes delivered under the water level. The tubes of this latter form of boiler are sometimes called "drowned" or immersed tubes; and M. de Chasseloup-Laubat has placed the two kinds of boilers respectively under classes which he terms "non-reversible cycle" and "reversible cycle" boilers. Mr. Thornycroft carried out these experiments in apparatus represented by Figs. 112 and 113, and described them as follows: "Considering the boilers shown in Figs. 112 and 113, if the pressure in the lower vessel—that is, at the bottom ends of the generating tubes—is that due to the full depth of water in the boiler, in addition to the steam pressure, then any reduction of density in the generating tubes will all be available for causing circulation; and thus any reduction in pressure in the lower vessel, below that due to the head of water in the boiler, is a direct loss to the energy of circulation, so that variations of this pressure are of great importance. These variations can be conveniently measured by a pressure column formed of a long gauge glass connecting the steam space of the upper vessel with the lower vessel. The difference of the water level in this glass from the water level in the upper vessel is a direct measure of any reduction of pressure in the lower vessel.

"I have made experiments, taking observations from such pressure columns fitted to the boilers shown in Figs. 112 and 113 when they were working under different conditions. The rate

[1] On "Circulation in the Thornycroft Water-tube Boiler," Vol. xxxv., p. 287. On "The Influence of Circulation on Evaporative Efficiency of Water-tube Boilers," Vol. xxxvi., p. 40.

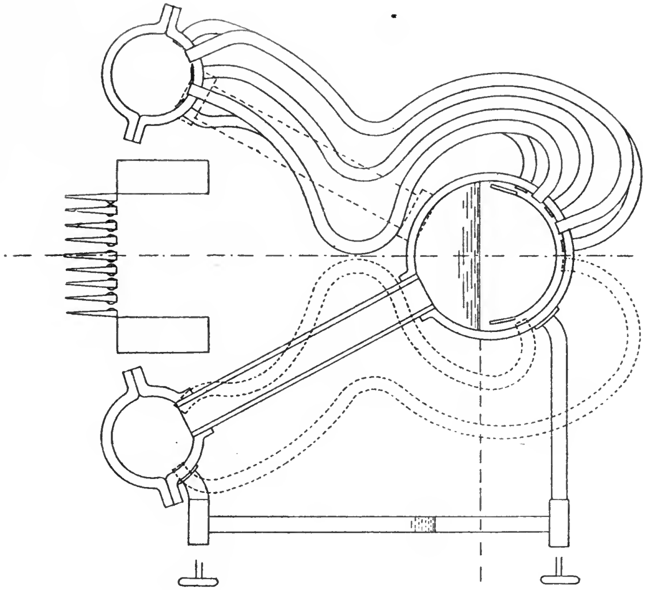


FIG. 112.

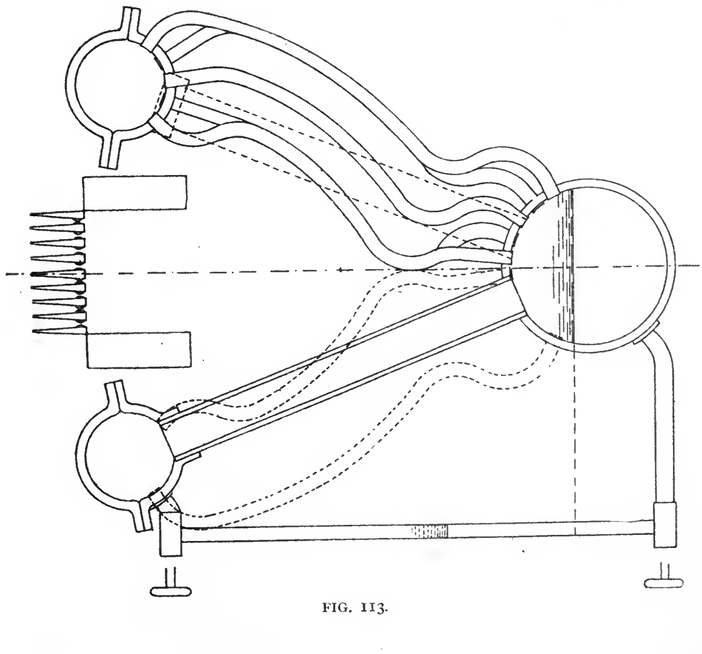


FIG. 113.

of evaporation and steam pressure being varied for the several arrangements of boiler, which were—

"(1) Generating tubes delivering above water.

"(2) Generating tubes delivering below water.

"(3) Generating tubes delivering below water without any special downtake tube.

"The curves in diagram Fig. 114 show graphically the results of these experiments; the falls of pressure in the lower vessels are plotted as ordinates, and the rates of working as abscissæ.

"It will be seen that the rate of working has been taken up very high, probably more than double ordinary working, the object in doing this being to ascertain up to what rate each arrangement can be worked with safety.

"In the first series of curves, the results recorded were obtained from the boiler (Fig. 112) with the generating tubes delivering above water. It will be seen from the curve that, as the rate of working is increased, the pressure column falls slightly, and at an evaporation of 20 lbs. of water per square foot of heating surface stands at 85 per cent. of the maximum; and by halving the working pressure the results are not sensibly changed.

"The next series of curves is taken from the boiler (Fig. 113), which has the same heating surface, etc., as Fig. 112, but the top ends of the tubes deliver below water. It will be seen that the curves fall much more rapidly than the first series, and that by halving the working pressure the pressure in the lower vessel is distinctly reduced. The third series was obtained from the same boiler (Fig. 113) by plugging the down-tubes, so that some of the generating tubes had to act as down-tubes for the supply of the others; the feed water being all delivered into the upper vessel. In this case the character of the curves changes from the first two series very much. A diminution in pressure of working causes the pressure column to fall very much; in the case of the pressure being only 28·75 lbs. per square inch absolute, it fell to about 46 per cent. of the maximum.

"The most important point, however, apart from this low pressure, but a result of it, is that for any given pressure a critical rate of working is arrived at when the pressure column begins to rise again with increased rate of working, thus showing an increased pressure in the lower vessel, caused by the

steam being unable to get out at the top ends of the tubes fast enough, and so comes out at the bottom ends as well.

"It will be seen from the curves that the lower the pressure of working the sooner this critical point is arrived at, and I found that when the evaporation was pushed beyond this critical point the tubes were not safe from overheating; but, by taking the tubes intended for downtakes, and extending their upper ends above the water surface so that water could not go down, and the steam in the lower vessel could readily get away to the separator, it was possible to increase the rate of evaporation somewhat, inasmuch as the facility for the tubes getting rid of their steam was increased.

"Contrasting the different conditions of working of the water-tubes in the three series of experiments I have described, and noting what slight differences these conditions may necessitate in the design of a boiler, the nearness to success which a boiler intended for hard forcing may be, and yet fail, is clearly seen.

"In conclusion, I would submit that the absence of special down-tubes limits to a great extent the amount to which a boiler can be safely forced, and shows that to obtain the highest rate of working with safety and efficiency these special down-tubes must not be neglected; and still further, the tubes should deliver above water, as then the circulation, as I have previously shown, is double that when the tubes deliver below water. So that this rapid circulation is a most important condition for hard working."

In his previous paper (read in March, 1894), Mr. Thornycroft said that he had "recently made experiments on the relative circulation of boilers when the generating tubes deliver above the water in the separator and below it," and had "found that, in the case where they deliver above, the circulation is rather more than double that when they deliver below." "The method of measurement I adopted," he continued, "was to put a rectangular notch, similar to those usually employed in gauging small streams, across the separator, so that all the water that went down the downtakes had to pass over it, and I then observed the flow over the notch through a glass window in the end of the boiler, and thus, knowing the size of the stream, was able to calculate the circulation. I found that, in the case of the above-water delivery, the circulation was 105 times the

feed—that is to say, for every pound of steam brought up by the generating tubes, 105 pounds of water are also passed through them." This was, however, modified at a later date by Mr. Thornycroft saying[1] that "*if the water going down the small tubes*, which should not go down, *was neglected*, the flow in the tubes delivering above water was about twice as great as the flow in the tubes delivering below." This is an important qualification, for it is only in the boiler with tubes delivering below water that any water *could* go down the small tubes, and it is impossible to say how many of these might act (or might have acted) as down-comers during such experiments, or what effect that might have on the rate of flow of water towards the downtake tube at the end of the separator. On this account the conclusion as to the proportionate flow of water in the two instances *as observed* is not very convincing; and another element of uncertainty is added in the fact of the flow of water having to be observed end-on (*i.e.*, in the line of and not across the line of advance of the water) from the glass window in the end of the separator, under circumstances in which a regularly flowing stream could not be expected, whilst all variations in speed of the current had to be estimated by the eye in the position mentioned.

The measurement of flowing water by means of bays or weirs is in reality a very delicate operation, and there are numerous sources of error connected with it. The coefficients differ with the depths of water, the width of canals of approach, the depths from the bottom of canals to the bottom edges of the weirs, the length and thickness of the weirs, and other circumstances. We have it, for instance, on the authority of Messrs. Donkin and Salter,[2] that an error of $\frac{1}{500}$ of an inch in excess (in measurement of the head of water over the bay in his experiments) in reading with $1\frac{1}{2}$ inch of water running over the bay would have increased the theoretical quantity by 0·2 per cent.

Normand's Objections.—M. Normand dissented from the conclusions founded on these experiments on other grounds. He said[3]:—"With all due deference, may I be allowed to state that

[1] See Trans. Inst. N. A., Vol. xxxvii., page 137.

[2] Min. Proc. Inst. C. E., Vol. lxxxiii., 380. See also lxxix., 402; cxiv., 333.

[3] "On Water tube Boilers." Trans. Inst. N. A., Vol. xxxvii., page 112.

I draw from these trials entirely opposite conclusions? The dimensions of the outside return tubes being similar in both cases, and admitting that the total return of water takes place by these tubes, and not partially through some of the heating tubes which may be less exposed to the fire (which does not seem to be a very reliable arrangement), it is clear that the quantity of water which goes down through the return tubes will be proportional to the square root of the difference of pressure between both reservoirs. Now, this quantity of water is, by hypothesis, exactly equal to the ascending water, so that it is, according to the trials, greater in the boiler where the upper ends of the tubes are under water. This conclusion is in accordance with the following probable theory, that the head of water which causes the circulation in a tube rising above water must be reduced by a height equal to that of the tube above the water level, due allowance being made for the smaller density of the fluid. The under-water arrangement does not, perhaps, allow of so great a heating surface for a given encumbrance, but it offers the further advantage that no 'steam chamber' can exist in the upper part of the tubes."

There are, in fact, other elements which should also enter into the consideration of such a question. For instance,[1] in the two boilers experimented with, the distance between the upper and lower vessels was least where the length of the bent water-tubes was greatest in one boiler, and *vice versa* in the other. That is to say, in the one which showed the smallest fall of water level, the water had the longer distance to ascend and the shorter to return, whilst the other presented the opposite conditions. It is evident that the variation of water level was caused by a more rapid circulation in the boiler which showed the greatest fall in the test column, unless we are to believe that longer and more crooked tubes offer less resistance to the flow of water than the shorter and straighter ones.

The slower the circulation, the larger the quantity of water which would be comparatively quiescent in the lower vessel or chamber, and therefore able to maintain the water column at its original level. But if all the water were in rapid and violent circulation, that would in effect be equal to an enlargement of

[1] "On Water-tube Boilers," by F. J. Rowan. Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xli., p. 29.

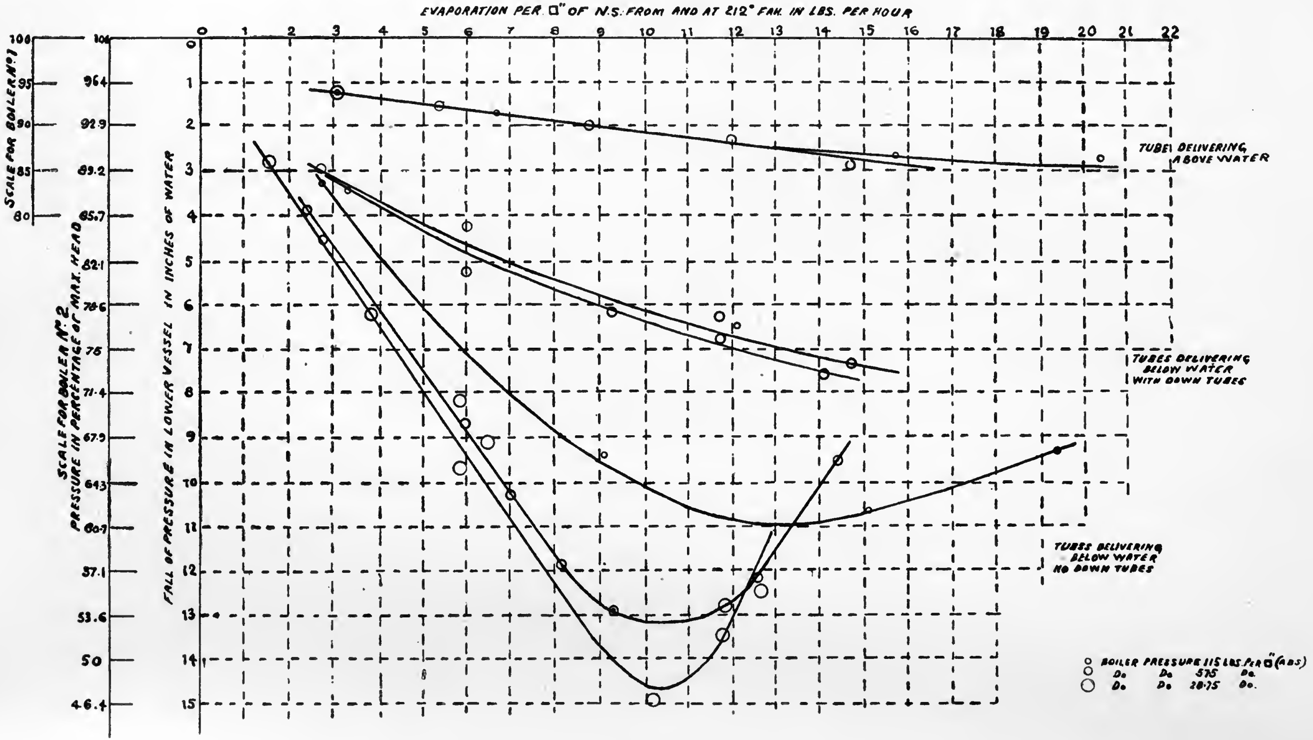

EVAPORATION PER □" OF N.S. FROM AND AT 212° FAH. IN LBS. PER HOUR
SCALE FOR BOILER Nº 1
SCALE FOR BOILER Nº 2
PRESSURE IN PERCENTAGE OF MAX. HEAD
FALL OF PRESSURE IN LOWER VESSEL IN INCHES OF WATER
TUBES DELIVERING ABOVE WATER
TUBES DELIVERING BELOW WATER WITH DOWN TUBES
TUBES DELIVERING BELOW WATER NO DOWN TUBES
BOILER PRESSURE 115 LBS. PER □" (ABS)
Do Do 57.5 Do.
Do Do 28.75 Do.

FIG. 114.

the steam space, because a large quantity of the water would be always broken up into the state of foam, and this would lower the level in the test column. It seems to be clear that in neither of these cases could the test column be taken as the equivalent of a piezometer.

Since the above was written, the view therein expressed has been fully confirmed by a paper read to the Inst. C. E. by Mr. J. T. Milton, Chief Engineer Surveyor of Lloyd's Registry.[1] Mr. Milton says of these experiments of Mr. Thornycroft's: "In the experiments made at two different steam pressures and at rates of evaporation varying between 3lbs. to over 15lbs. per hour per square foot of heating surface, the reduction of pressure in the lower chambers was in every case from two and a half to three times as great in the boiler where all the tubes delivered below the water as in that in which they delivered above the water. The velocity of the water in the down-comers must, therefore, have been between 60 per cent. and 70 per cent. greater in the former than in the latter, and therefore far more water must have circulated through the up-tubes. This should have been expected, as in the boiler with the above-water delivery, owing to the greater height the mixture of steam and water has to be raised, its density must be lighter, or the pressure to raise it must be greater, or both of these must act together. A lower density with the same amount of steam evolved must imply less water circulating with the steam."

Blechynden's Experiments.—It was known that the late Mr. Blechynden was engaged on some experiments on circulation of water in boilers, the results of which, it was feared, would have been lost to the profession in consequence of his untimely death. Happily, however, Mr. Milton, in his paper on "Water-tube Boilers for Marine Engines" (Min. Proc. Inst. C. E., Vol. cxxxvii., pp. 178–180), places on record an account of these experiments obtained from Mr. Billetop, who carried out the work for Mr. Blechynden. Mr. Milton says: "These trials are especially valuable because they were made upon a full-sized boiler, not upon models. The boiler, Fig. 115, had a grate surface of 37 square feet, and a total heating surface of 2,445 square feet. Besides the

[1] On "Water-tube boilers for Marine Engines." Min. Proc. Inst. C. E., Vol. cxxxvii., p. 167.

small generating tubes, which were one inch in external diameter, the upper and lower chambers were connected by eight stay-tubes, $1\frac{1}{4}$ inches internal diameter, which were placed outside the casing, and which could not be shut off nor plugged, and also by a 5-inch internal diameter down-pipe to each bottom chamber, these being so arranged that they could be shut off when required. The feed-water could be delivered either into the upper chamber, through an ordinary full-length perforated internal feed-pipe entirely submerged, or into the two lower chambers, which were also fitted with internal pipes. Special gauge-glasses were fitted, as shown in Fig. 115, to allow the

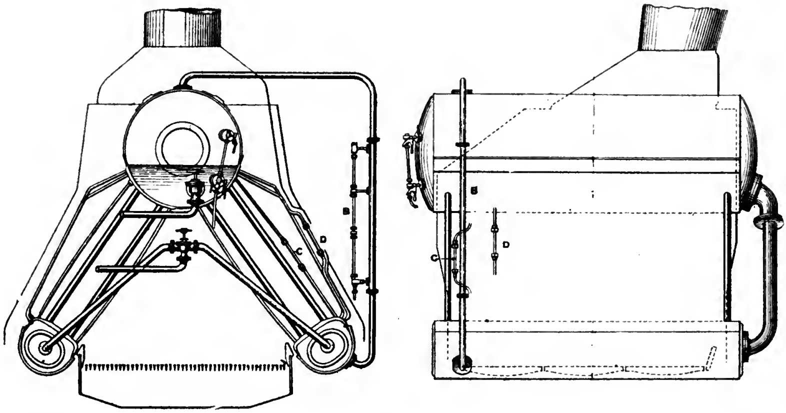


FIG. 115.

direction of the current in the outer rows of tubes to be observed, and also to show the reduction of pressure in the lower chamber under the different conditions of the various experiments. So far as feeding was concerned three distinct sets of experiments were made : (1) with the feed in the upper chambers ; (2) with the feed in the lower chambers ; and (3) with the feed shut off entirely ; the last experiments, however, could be made for short periods of three minutes or four minutes only.

"When the feed is delivered into the upper chamber it mixes with the water there, which is at the boiling point, and comes into contact with some of the steam generated, so that before it reaches the down-coming tubes its temperature will be raised

considerably, possibly to nearly the boiling point. If any of the generating tubes act as down-comers, the water in them will be further heated on its way to the bottom chamber, so that the temperature of the water in the bottom chambers may be nearly that of the boiling point. When, however, the feed enters the lower chambers direct, the water in them will be of considerably lower temperature than boiling point. If the feed is shut off for a few minutes all the water in the boiler will be raised to the boiling point. If the water first entering the up-tubes is at boiling point steam bubbles will be formed in these tubes along their whole length, whereas if the water enters at a less temperature, the first part of the length of the tubes will be occupied in raising the temperature of the water to boiling point, and only in that part of the tube above this will bubbles be formed. The average density of water in the up-tube will therefore be greater when the feed is placed in the lower chambers, and there will be less reduction of pressure in the lower chambers. Another way of considering the matter is that when the feed enters the lower chambers all the steam produced in the tubes is available for the engine; while when it enters the upper chamber, some part of the steam made in the tubes is employed in heating the feed-water nearly up to the boiling point. In the latter case, therefore, with the feed in the upper chamber, if the output of the boiler is the same there will be more steam, and, consequently, relatively less water in the generating tubes. This will cause a greater loss of pressure in the lower chamber.

"The actual results of loss of pressure in this lower chamber during a series of experiments made with this boiler are shown in Fig. 116. Curve No. 1 gives the results of four experiments made at different rates of evaporation with the special down-pipes open, and the feed entering at the bottom. No. 2 gives the results of two experiments under similar conditions, but with the feed entering the top chamber, while No. 3 gives the results of trials made with the feed shut off for short periods. It will be seen that all three curves are slightly convex downwards, in this respect being similar to those representing Mr. Thornycroft's results. The fall of pressure in the lower chamber, due to introducing the feed in the top chamber, is very marked. Curve No. 4 gives the results of three experiments made with the special down-comers shut off and the feed entering at the

top. The difference between curves No. 2 and No. 4 is therefore due entirely to the effect of the large outside pipes.

"In all the experiments the gauge-glass D, Fig. 115 showed that in the wall-tubes the current was downwards when the water level was above their upper ends. It was also always downwards in the glass C in all three experiments without the outside large tubes, and in the other experiments it was generally downwards also, as only on one or two occasions was the current observed to be reversed. When the outside tubes were shut off and the boiler was much forced for a few minutes, the feed entering the top and the water maintained at the ordinary level in the ordinary gauge-glass, the water in gauge-glass B fell out of sight

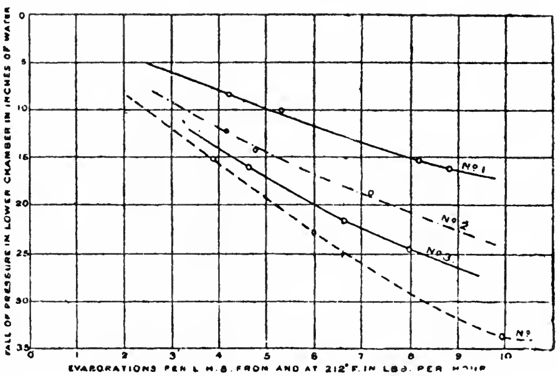


FIG. 116.

altogether, and an accumulation of steam was formed in the lower chamber. This was demonstrated by opening a cock fitted to the chamber, but it is needless to state that this experiment was not continued very long."

Mr. Milton remarks that "there is difference of opinion as to the advantage or necessity of a high speed of circulation of the water in a water-tube boiler; but that it is agreed that the inner surfaces of the tubes should always be kept wet to prevent overheating, so that a considerable proportion of water should always be in them and not steam alone, especially in those tubes exposed to the fiercest action of the fire." Mr. Blechynden's experiment of forcing the boiler, without the large down-tubes, showed that "at very high rates of evaporation there is a

possibility of all the water being driven out of some of the tubes, but it will require much greater forcing to do this when large down-tubes are fitted or when the feed is entered into the lower chambers." In actual trials at sea with the Blechynden type of boilers, "at high powers there was a considerable amount of priming when the feed was entered in the upper chamber. After the feed pipes were altered to enter the lower chambers, there was no further trouble in this respect."

Appliances for Measuring Circulation.—No satisfactory appliances for the measurement of the quantity of water circulating in given time, or for indicating the velocity of the water circulating under the action of the natural process of boiling, have as yet been introduced. Mr. Thornycroft's method has just been referred to. Another was introduced in 1881 by Mr. Thielmann.[1] This consisted of a fan or propeller wheel fixed in the rear circulating tube or down-comer of a Steinmüller form of boiler. The relative dimensions of down-comer and propeller are unfortunately not given, but it is stated that under test the propeller for each 100 revolutions passed 40 litres of water. When the boiler was under steam, the propeller revolved at the rate of from 380 to 420 revolutions per minute, showing that from 152 to 168 litres[2] of water were passing through it per minute. This was equal to from 7·5 to 8·4 litres per square metre of heating surface. The actual evaporation of the boiler was 20 kilos[3] per hour per square metre of surface, which amounted to about 4·5 per cent. of the water circulated. The total quantity of water contained in the boiler was 450 litres, which quantity was circulated every three minutes.[4] This is a very interesting method of observing the circulation, but it is evident that it demands that no water shall descend by any other passage than the appointed down-comer. It has also the disadvantage that the propeller cannot be put out of action except by removing it from the boiler, which necessitates the opening up of the boiler. To be thoroughly serviceable such apparatus should be capable of being rapidly

[1] "Handbuch über Vollständige Dampfkessel Anlangen." See Mr. G. W. Thode's remarks in Trans. Inst. Eng. and Shipbuilders in Scotland, Vol. xli., p. 142.

[2] 1 litre = 2·20 lbs. of water at 62° F., or ·220 of a gallon.

[3] 1 kilogramme = 2·2046 lbs.

[4] Mr. G. W. Thode was kind enough to furnish the author with this information.

connected with and disconnected from the interior of the boiler, and should introduce the minimum of parts or obstructions there.

The gauge-glass system for indicating the difference of pressure between the top and bottom chambers of a boiler would, if it could be relied upon, answer these requirements in a satisfactory way. But neither in the form in which Mr. Thornycroft introduced it in the experiments referred to, nor in the modification shown by Professor Watkinson is it sufficiently free from probable error.

The latter was illustrated and explained to the Institution of Engineers and Shipbuilders in Scotland[1] as follows: "This was shown in Fig. 117, and consisted of an upper and a lower drum connected by one down-comer *a b* and one up-comer *c d e*. Open-topped gauge-columns g and g^1, were fixed to the upper and lower drums respectively. The column g showed the level of the water in the upper drum, and column g^1 measured the pressure in the lower drum. When circulation was set up by applying heat to the up-comer, or by admitting air to the lower end of the up-comer, the surface of the water in the column g^1 would fall, and it was evident that the difference between the levels of the water in the two gauge-columns was the head available for circulation if the temperature in the columns had been maintained the same. If the temperature of the water in the columns had not been maintained the same, then a correction had, of course, to be made on that account. As the corrected difference of levels was the head available for circulation, the velocity of flow through the down-comer was proportional to the square root of the corrected difference of level. The mass of water that flowed through the down-comer per second was

$$= \sqrt{2gh} \times A \times C \times M \text{ lbs.}$$

h being the corrected difference of levels in feet.
A being the area of the down-comer in square feet.
C being the coefficient of discharge for the pipe.
M being the mass of 1 cubic foot of water in lbs.

In the experiments which he (Professor Watkinson) had made, in order to eliminate possible errors in the determinations of A,

[1] Transactions, Vol. xli., pp. 250-252. See also Trans. Inst. N. A., Vol. xxxvii., pl. xlviii., Fig. 7.

M, and C, he had disconnected the up-comer *d e*, plugged the hole *e*, and then syphoned hot water into the upper drum,

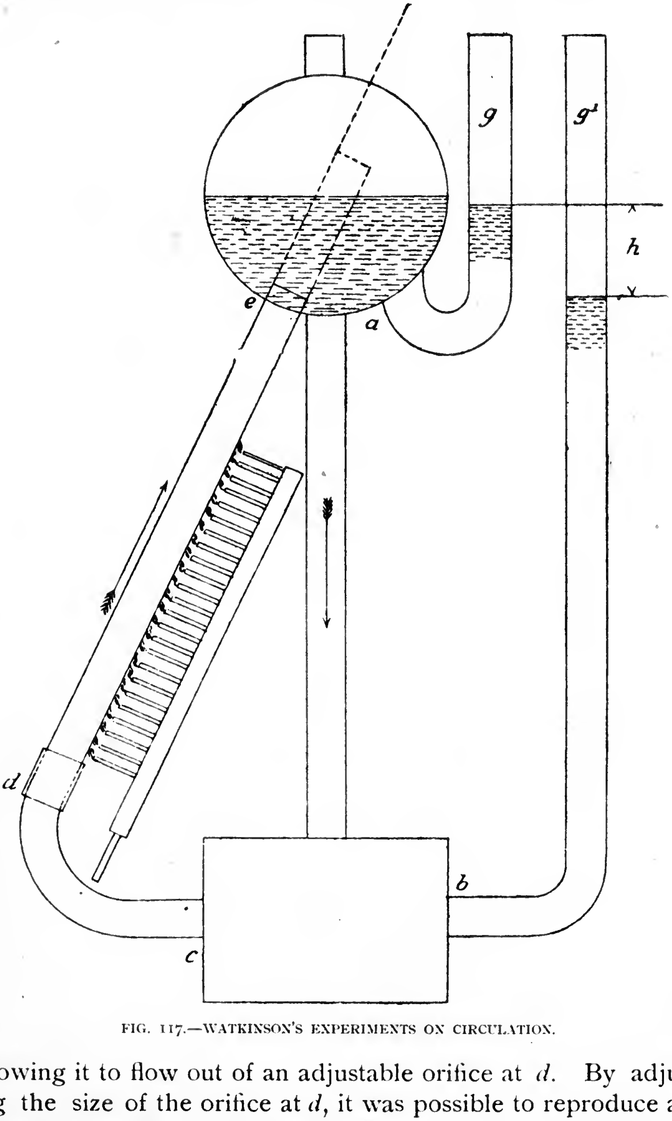


FIG. 117.—WATKINSON'S EXPERIMENTS ON CIRCULATION.

allowing it to flow out of an adjustable orifice at *d*. By adjusting the size of the orifice at *d*, it was possible to reproduce any deflection of the gauge-column g^1 which had been obtained in

the ordinary experiments. By proceeding in this way, and weighing the water which flowed out at d, he had been able to determine very accurately the mass of water flowing through the down-comer per second, for different deflections in the gauge-column g^1. In that way he had found that the ratio of the mass of water circulating per second, to the mass evaporated per second, varied in the model, at the usual ratio of working, from about $\frac{50}{1}$ to about $\frac{250}{1}$ according to the size of the down-comer used. When the latter value was obtained, the area of the down-comer was approximately equal to the area of the up-comer. He had also used the same model in order to determine whether there was any gain in the velocity of the circulating water due to discharging that water above the water level into the upper drum. . . . He had found that when the usual ratio of area of up-comer to area of down-comer was adopted there appeared to be a gain of 3 or 4 per cent. in favour of the above-water discharge."

Defects in Watkinson's Apparatus.—"Open-topped gauge-columns" are, of course, applicable only to boiler models or boilers worked at atmospheric pressure, but even for such applications it is not at all certain that as registers of "pressure," or more properly of hydrostatic head, they would always give indications which could be relied upon. If, for instance, the area of the discharge orifice were greater than that of the down-comer, the level of water in the gauge-glass g^1 connected with the bottom chamber would necessarily fall, and that gauge-glass might even be almost empty, but that would result from inadequacy of supply to the bottom chamber. Where that chamber had, however, a sufficient capacity such a result would be prevented. In fact it is apparent that the capacity of that chamber must exercise the greatest influence on the indications of the said gauge. Professor Watkinson admitted that the area of the down-comer exerts a decided influence on the result, so that the more that area is diminished from equality with that of the up-comer the smaller is the velocity of circulation. But as the experiment with the plugged up-comer and the water flowing out at d (simply by gravity) shows, the gauge-glasses can at the best indicate only the rate at which the water *descends*, so that we might readily have a case in which more water was being

carried up by ebullition than was able to flow down by the down-comer in a given time, and hence the gauge-glasses would give a false indication of the condition of circulation where such elements were present.

Theory of the Piezometer.—There does not seem to be any good reason why the velocity should not be directly measured in relation to the pressure which is due to the motion of the water. It is well known that the hydrostatic pressure in a pipe containing still water can be shown by inserting an open tube of any shape in the pipe. The water rises in the tube to a height h, whence the pressure is known to be $P = wh$ lbs.[1]

If, however, the water is flowing with a velocity V in the direction of the arrow, and two tubes shaped respectively as A B and C D in Fig. 118 are inserted in the pipe, then there will be a difference of level in these tubes, that in A B being lower than C D. The difference of level between C and A has been found to be $\frac{V^2}{2g}$ (feet) but "the real pressure in the pipe is shown by the tube A B, and the extra height of the column in C D is due to the fact of the still water in C D at its open end stopping the flow of the water which meets it, just as the hand held still in a running stream stops some water, and hence a pressure is felt. If there were no loss of head, C would be then on the same level as the water surface of the reservoir. The tube A B is called a piezometer, and we must always be careful to see that it is quite parallel to the direction of flow."[2]

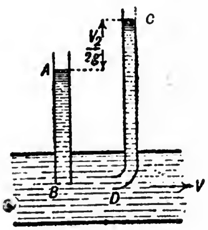


FIG. 118.

[1] P = pressure per sq. foot due to head.
w = weight of 1 cubic foot of water in lbs.
h = height in feet (*i.e.* "head").

$$P = wh \text{ lbs.}$$

1 cubic foot of fresh water weighs 62·5 lbs.
1 cubic foot of sea water weighs 64 lbs.

Thus a head of 1 ft. of fresh water = 62·5 lbs. per square foot.

$$= \frac{1}{2·3} \text{ lbs. per square inch.}$$

$$1 \text{ ft. of sea water} = \frac{1}{2·25} \text{ lbs. per square inch.}$$

1 inch of mercury = ·49 lb. per sq. inch.

[2] Cotterill and Slade, "Lessons in Applied Mechanics," p. 475. London, Macmillan, 1891.

Torricelli's Theorem.—Professor Greenhill remarks in his "Treatise on Hydrostatics" that, "the velocity v of discharge of water from a small orifice a depth h below the free surface was given by Torricelli (1643) as the velocity v acquired in falling from the level of the free surface, so that

$$\tfrac{1}{2} v^2 = gh, \text{ or } v = \sqrt{(2gh)}$$

and v is then called the velocity, due to the head h. This is argued by asserting that the hydrostatic energy of the water Dh foot-lbs. per cubic foot, or h foot-lbs. per lb., becomes converted, on opening the orifice, into the kinetic energy

$$\tfrac{1}{2}\, \mathrm{D}v^2/g \text{ ft.-lb./ft.}^3, \text{ or } \tfrac{1}{2}\, v^2/g \text{ ft.-lb./lb.}$$

Bernoulli's Theorem.—In Bernoulli's Theorem the gradual interchange of the energies due to pressure, head and velocity in a stream line filament in the interior of the liquid, or in a smooth pipe of gradually varying section, is expressed by the equation—

$$p + \mathrm{D}x + \tfrac{1}{2}\, \frac{\mathrm{D}v^2}{g} = \mathrm{D}h, \text{ a constant,}$$

$$\text{or } \frac{p}{\mathrm{D}} + x + \frac{v^2}{2g} = h, \text{ a constant,}$$

when p denotes the pressure, D the density, v the velocity, and x the height above a fixed horizontal plane. Thus, with British units, the total constant energy Dh along a stream line is in foot-lbs. per cubic foot, and composed of p due to the pressure, Dx to the head, and $\frac{\frac{1}{2}\mathrm{D}v^2}{g}$ due to the velocity; or in foot-lbs. per lb. the energy or head h is composed of $\frac{p}{\mathrm{D}}$ due to the pressure, x to the head, and $\tfrac{1}{2}\, v^2/g$ to the velocity.

"Bernoulli's Theorem is illustrated experimentally in Fig. 119 by an apparatus devised by Froude[1]; a tube of varying section carries a current of water between two cisterns filled with water to nearly the same level, and the pressure is measured by the height of water in small vertical glass tubes called *piezometer*[2]

[1] British Association Reports, 1875.

[2] For piezometers consult Proc. American Academy of Arts and Sciences; "Experiments upon Piezometers used in Hydraulic Investigations," by Hiram F. Mills, Civil Engineer, Vol. xiv., page 26; Min. Proc. Inst. C. E. lxi. 408. See also "Experimental Investigation of the Theory of the Pitot Tube," etc., by A. Rateau, Prof. at the School of Mines, St. Etienne, Annales des Mines, 1898, series 9, Vol. xiii., p. 331; also Trans. of the Inst. of Mining Engineers, Vol. xvii. p. 124.

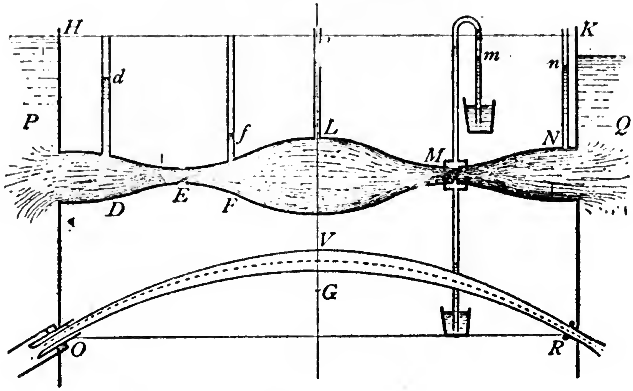


FIG. 119.

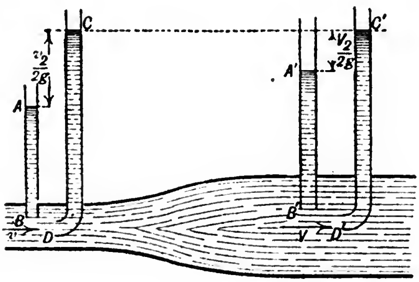


FIG. 120.

tubes ; and it is found, in accordance with Bernoulli's Theorem, that the water stands higher where the cross section of the current is greater, and the velocity consequently less." This is a possible explanation of the differences of level in the gauge-glasses in Mr. Thornycroft's experiments, though it is difficult to see how these columns form true piezometers. "If the velocity at the throat E is that given by Torricelli's Theorem, the pressure there is reduced to atmospheric pressure, and the tube can be removed in the neighbourhood of E, as at the throat of an injector jet. At M the cross section is less than at E and the pressure is below atmospheric pressure, so that water will be drawn up in a curved piezometer tube, like a syphon. By the observation of the heights in piezometer, at L and N as well, the velocity of flow can be inferred, knowing the cross section of the current."

A very simple explanation of this last point is given in Cotterill and Slade's "Applied Mechanics." Taking the case of a pipe, shown in Fig. 120, the section of which varies gradually, tubes A B, C D, A^1 B^1 and C^1 D^1 are placed in it, and by means of these the changes of velocity and pressure, which take place on account of the sectional area not being constant, are shown, although the whole pipe is subject to the same "head."

"Let V = velocity at B D, V^1 = velocity at B^1 D^1

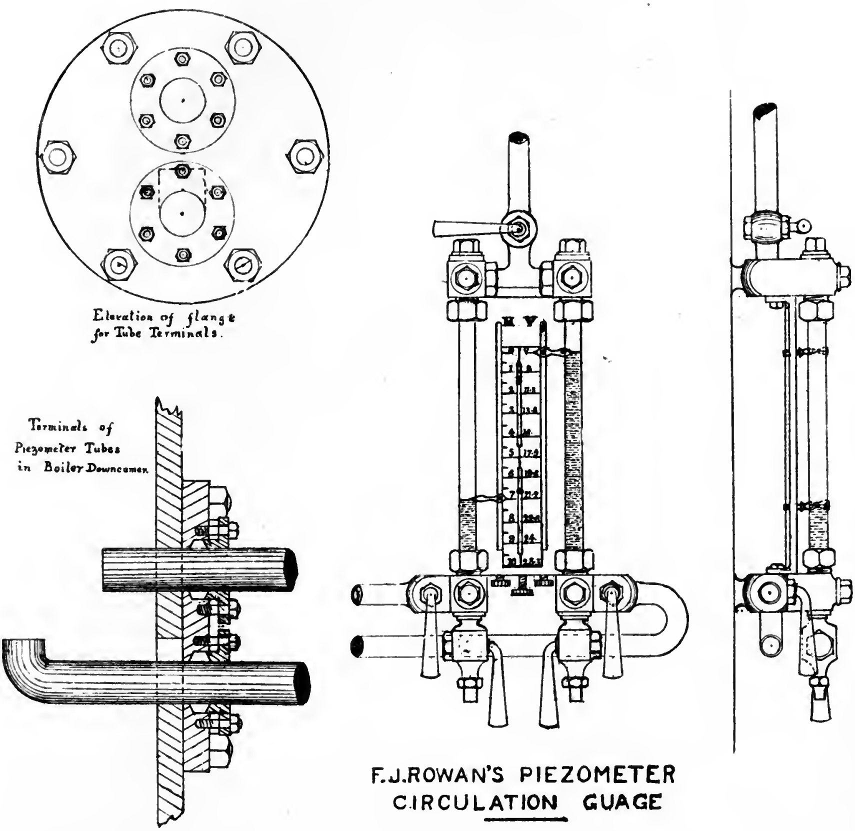
A = sectional area at B D, A^1 = sectional area at B^1 D^1

Then the most plainly evident thing, perhaps, that we know about the flow is that exactly as much water must flow past B in one second as flows past D in the same time, and hence

$$V A = V^1 A^1,$$

so that if we know the velocity at any one point of a given pipe, we can at once determine it for any point whatever.

Next C and C^1, being both on the level of the water surface in the reservoir, are both on the same level. But A is $\frac{V^2}{2g}$ feet below C, while A^1 is only $\frac{V'^2}{2g}$ feet below C^1 ; whence it follows that A^1 is $(V^2—V'^2)/2g$ feet above A, and the pressure at B^1, which would in still water be greater than at B by an amount wz—supposing B^1 to be z feet below B, *i.e.*, the head over B^1 z



F.J.ROWAN'S PIEZOMETER CIRCULATION GUAGE

FIG. 121.

feet more than over B—is now still further increased by the pressure due to $(V^2—V'^2)/2g$ feet of head.

"If the pipe be level, then z vanishes, and we see that in a level pipe the pressure increases as the velocity diminishes, *i.e.* as the sectional area increases. This result appears at first sight strange, and is often disputed by persons not properly acquainted with the elements of the subject. The objection is, of course, based on a misapprehension, being usually put something in this form: In the small part of the pipe the water must be more crowded together, and hence the pressure must be greater. The idea present here is plainly that of a crowd of people moving through a narrow passage between broader spaces, and where the analogy fails is in the fact that the velocity does not increase through the narrow part; those behind actively push, which we must remember a particle of water cannot do, and thus prevent those in the narrow part from moving at a rapid rate."

Now, although all these illustrations and arguments are concerned only with open-topped pipes at atmospheric pressure, yet there seems to be no reason why the same action should not take place where both the tubes are subjected to the same steam pressure.

Rowan's Velocity Gauge.—Fig. 121 shows an instrument devised by the author) by which the velocity of the current of water in the part to which the tubes are attached may at any time be read off.

It is founded on a direct application of the theory of the piezometer to the problem in hand. Between the gauge-glasses connected with the piezometer tubes, which have a common connection above to the steam space, there is a movable scale, divided into inches and parts of an inch on one side, with the corresponding velocities inserted opposite these figures worked out according to the formula, $v = \sqrt{2gh}$. The quantity of water flowing per second can readily be ascertained from this when the sectional area of the tube or passage with which the gauge is connected is known.

M. Chasseloup-Laubat's Calculations.—M. L. de Chasseloup-Laubat published an examination of the principles of circulation in as far as they applied to water-tube boilers, of what he termed "reversible" and "non-reversible" cycle classes, in which the movement of the water was that which was produced by the

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natural action of boiling. The following summary of his examination of the subject was communicated by its author to the Institution of Engineers and Shipbuilders in Scotland :—

(1) "In a liquid of known scientific weight, a bubble of steam of known specific weight and volume, occupying a position situated at a known distance from the free surface of the liquid, corresponds to a determined potential energy.

(2) "The yield of this potential energy in circulating work when the bubble rises to the surface—*i.e.*, the useful work (from the point of view of circulation) resulting from the transformation of this potential energy—is not constant. It is, on the contrary, variable. It is equal to the theoretic work multiplied by a coefficient varying between 0 and 1. This coefficient is itself given by a very complex function of numerous elements, such as absolute diameter of the tubes, absolute diameter of the bubbles, quality of the water, intensity of the heating, etc. I have only been able to show the existence of this complex function without managing to determine the relative value of its constituent elements.

(3) "I have divided the water-tube generators into two principal classes, which I have termed 'reversible' cycle and 'non-reversible' cycle, according as the tubes heated have their outlet below or above the free surface of the water in the upper collector.

(4) "I have shown that for the reversible cycles the normal circulation was always continuous, whilst for the non-reversible cycles it was generally pulsatory.

(5) "I have shown that, leaving out of account the friction and supposing the case of plug bubbles almost completely closing the tube, the maximum weight of fluid—steam and water—discharged in given time per unit of section of heated tube was attained. That is a new argument in favour of the use of very high working pressures, and a means of calculating the maximum of specific heating compatible with the security of the apparatus. If this maximum volume of steam be exceeded in the tube heated, the circulation may become irregular and pulsatory and diminish in intensity, in which case the apparatus may be endangered.

(6) "For the non-reversible cycles, theory and experiments together show that continuous circulation can hardly exist

except with certain qualities of water—brackish, for example—which facilitate the formation of a sort of emulsion or intimate mixture of water with a very great number of very persistent little bubbles. More generally, with ordinary water, the circulation is pulsatory—that is, it is effected by alternate discharges of plugs of water and of steam, or, more correctly, by plugs of steam separated by a mixture of water and steam. In this case I have not been able to calculate the maximum of circulation.

(7) "The conclusion is, that (*a*) the first cause of all circulation is evidently the potential energy of gravity, resulting from the formation of bubbles of steam in the midst of the liquid mass. (*b*) The rule of mean specific weights—which evidently gives the work available to produce the circulation—does not give the effective work which produces this circulation. The second is equal to the first, multiplied by a coefficient varying between 0 and 1. It is this which explains why, in certain water-tube apparatus of faulty construction, the general circulation is almost *nil*, all the available work being absorbed by local eddies and not by general circulation.

"This part of my theory has lately received an important experimental confirmation. M. Bellens, whose studies upon circulation are well known, has published in the *Revue Technique* of January 10th and 25th and February 25th, of 1898, three articles in which are given the results of a great number of experiments made with vertical glass tubes in which circulation was produced by the ascension of air bubbles. In the conditions which I have stated, the maximum discharge of water always took place when the volume of air was practically equal to the volume of water. M. Bellens found only about 10 per cent. difference between the results of theory and practice.

"As I have stated in the *Bulletin des Ingenieurs Civils de France* (of April, 1897), if we call Q the maximum weight of water—calculated by the formula I have given—which a tube is capable of discharging during unit of time, T the temperature of the steam, and N_s the total number of caloric units received by the tube during the same unit of time, there will be a serious danger each time that

$$N_s \geqslant Q\ (606{\cdot}5 - 0{\cdot}695\ T).$$

"This shows for reversible cycles, that is to say for the majority

of boilers, a maximum of specific working beyond which, contrary to the general opinion, things no more adjust themselves. The specific discharge diminishes ; the column of mixed water and steam travels slower and slower ; the circulation becomes pulsatory ; long plug bubbles drive the water completely out of the heated tube through both ends at once ; and finally the tube melts and bursts."

It is to be remarked, however, that M. Chasseloup-Laubat's calculations are occupied almost entirely with boilers composed of small water-tubes, so that his maximum amount of circulation is obtained when the steam bubbles form plugs or pistons which occupy the full section of the water-tube, but do not extend along the tube farther than to allow of a rapid succession of alternate water plugs of the same dimensions.

Larger quantities of steam do not increase the amount of water carried along through the tubes, but, on the contrary, diminish it, and produce the action described by Mr. Thornycroft[1] as incidental to ordinary circulation.

With tubes of larger diameter the formation of these plugs would not readily, if at all, take place, and hence the calculations do not wholly apply to them.

Moreover, the speed of circulation hitherto attained in any water-tube boiler is evidently insufficient for complete transmission of the heat, as evaporative results prove. It is only in a rare experiment that the results obtained in Thornycroft boilers have been surpassed, and these results show a velocity of circulation only sufficient for an evaporation of 20 lbs. of water per square foot of heating surface per hour—at any rate, in combination with the velocity then given to the gases. The same may be said of the boilers of M. Niclausse and M. Normand, although it is clear from his papers "On the Economy of Fuel in very Fast Vessels" and "On Water-tube Boilers,"[2] that the latter appreciated to some extent the importance of rapid motion. Either, therefore, the velocity attainable by natural circulation is insufficient, or the circulation is not constant and steady enough for the best result. It is necessary to repeat that the important question is not, What is the speed actually attained in any individual boiler ? but is, What is the best speed for the water in view

[1] Min. Proc. Inst. C. E., Vol. xcix., p. 46.
[2] Trans. Inst. N. A., Vol. xxxvii., p. 169 ; Vol. xxxvi.

of heat transmission? and this being known, what are the best means, consistent with the other elements of the problem, of producing this movement?

Forced Circulation.—It seems to be certain that mechanical means must be introduced in order to ensure a greater velocity of circulation and a more constant movement of the water than that which is due to the natural action of boiling. Under such altered circumstances, of course, such calculations as those of M. Chasseloup-Laubat become inapplicable. Various devices have already been introduced at different times with the object of securing regularity in the action and direction of the circulating currents, but none as yet for the purpose of obtaining greater speed.

Artificial Circulation.—The circulation resulting from the use of these devices has been termed *artificial circulation* in contradistinction to that which is due to the natural process of boiling, and it must be further distinguished clearly from *forced* or *accelerated circulation* such as is here proposed.

The difference between these methods (*i.e.*, natural and forced circulation) has already been emphasised in connection with the subject of heating by hot water by Mr. W. Anderson,[1] who remarked: "When the water circulates through the pipes by virtue of the difference of temperature of the flow and return currents only, it is impossible to count on a greater mean temperature of the pipes than from 160° to 180°. When forced circulation is adopted—as when the water is propelled by a centrifugal pump and is under a pressure of about 70 feet—a much higher temperature can be attained." In this case the increase of temperature may be partly due to the higher pressure in the pipes, but the improved result is no doubt also owing to the more rapid movement of the water produced by the pump.

Mr. J. G. Hudson remarked (in the *Engineer*, Vol. lxx., p. 483) that—"Heating water below its boiling point by steam is in some respects a parallel case to what takes place in a steam boiler. In each there is on one side of the surface a medium which, under normal conditions, transfers heat with great reluctance in comparison with the medium on the opposite side of the surface.

[1] Min. Proc. Inst. C. E., Vol. xlviii., p. 257.

"In the steam-heating apparatus the water is the sluggish medium, and in the boiler it is the hot gas. These resemble each other in being both very bad transmitters of heat by any method other than convection. In the case of heating water by steam, it can be conclusively shown that, other things being equal, the quantity of heat taken up by the water is almost wholly a question of the speed with which the latter traverses the heating surface, the transmission increasing only somewhat less rapidly than the speed. So important is this influence that the transmission has been found to vary from as little as 20 or 30 units per degree, where the water was confined in small tubes and moved very slowly, up to nearly 1,000 units, according to the speed."

Amongst the more important devices in use in connection with artificial circulation are the automatic feeds of Yarrow, Thornycroft, Belleville, and perhaps others, the automatic valves of Belleville and Solignac, and the "Emulseur" of Dubiau.[1]

The same result, viz., the regular feeding of the water to the evaporating surface, was obtained with the pumps supplying those boilers, such as the Boutigny, Serpollet, De Laval, Simpson and Bodman, and others, which are or were used to flash small successive quantities of water wholly into steam without expending heat in boiling and circulating a larger quantity. The boiler introduced by Mr. Benson in 1856 also had artificial or "mechanical circulation," as it was then called, and this was perhaps the earliest plan in which all the water in circulation in a boiler was passed through a pump. There was, however, no thought of an increased velocity of circulation in this plan, but the boiler being composed of several flattened spirals, as in the Belleville boiler of to-day, but composed of horizontally placed tubes of small diameter, the mechanical arrangement was adopted to ensure a steady movement of water throughout the whole length of the spirals, so that the tubes should not be burned, in consequence of shortness of water in some parts.

Forced Circulation.—There should evidently be a development of this system carried out, by which, not only will all the water in the boiler be circulated by means of a pump, but also the water will be propelled through the boiler passages, or over the

[1] See note Sur les Chaudières a Emulsion de Vapeur, par M. M. Jouffret, Mem. et Comp. Rend. de la Soc. des Ingenrs. Civils, January 7, 1898, p. 79.

heating surface, at a greater speed than that which is due to the natural action of boiling. The expenditure of power required for this operation will be trifling, because the same pressure being on both sides of the pump, the power required will be regulated simply by the quantity of water set in motion, its speed, and the height to which it is forced—some allowance being, of course, made for loss of power by friction.

In addition to the control of speed of the movement of water over the heating surface which this method gives, it also gives control of the direction in which the water is caused to flow. The results obtained with "film" evaporating vessels show how important this may be.

Film Evaporating System.—This system of evaporating has been tried in various forms, and carried to a very successful issue in the apparatus of Mr. James Foster,[1] who makes use of the form of tube shown in Fig. 122. The top of each tube is fitted with a liquor spreader or distributor chamber with bayonet catch attachment to the tube. This chamber has three legs or ribs with open spaces between, these legs resting on the top tube plate and the film tube being suspended from them. The liquor to be concentrated or boiled is fed into these chambers and runs down the annular openings in each of the three legs or ribs. It is then distributed or directed by the shields and runs down the inner

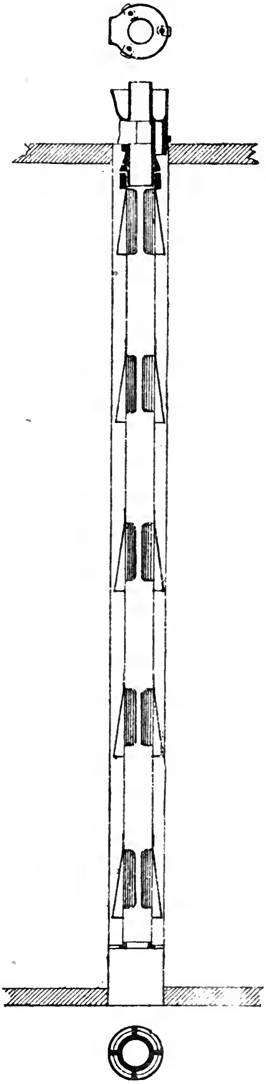

FIG. 122.

[1] "On Evaporation by the Multiple System," also Trans. Inst. E. and S., Vol. xli, p.141.

surface of the heating tube in a thin film or layer. The annular spaces between the shields and the heating tube are made larger at the top than at the lower end, because the quantity of liquid becomes smaller on account of evaporation as it descends. Each film tube of the usual length is fitted with five distributing shields, and as the liquid evaporates the vapour passes under these shields, through the openings in the film tube which are there, and up through the centre of the film tube to the top chamber. By such means the vapour can escape as it is formed and without priming water, whilst the whole surface of the heating tube is covered with liquid, which does not run down in rivulets. The usual length of these working tubes has been (in evaporating vessels) 4 ft. 2 in. over the tube plates, and $1\frac{7}{8}$ in. internal diameter, the film tube being placed inside of each heating tube. Although in these evaporating vessels steam is used as the heating medium, yet there is no danger of the heating tube being burned when exposed to the higher temperature due to the hot gases from a fire. Not only is ordinary evaporation sufficient to prevent such overheating, but further, a result noted in Miss Bryant's experiments (see Chap. IV., p. 185) shows that with a thin film of liquid the evaporation is quickened and the temperature of the metal heating surface is lowered even beyond the temperature found in the same surface when a larger quantity of water is present.

For an adaptation of the film-tube system to boilers, it is necessary to have forced circulation, because the water has to be continuously supplied to the main chamber at the top of the heating tubes, from which it enters the various distributor chambers of the tubes. The film tube is extended up to an upper division of the main top chamber, which is thus filled only with steam.

With forced circulation it is possible to ensure that the currents of water and hot gases travel in opposite directions, and although it is possible also to arrange this with natural circulation, yet the limit of velocity of movement is soon reached with that plan. In no other way can the velocity of circulation be controlled and the direction and quantity maintained steadily, than by the use of mechanical appliances for circulation of the water, just as they have been found necessary for proper control of the combustion and gases.

Critical Velocity.—A much less speed is required for water, however, than is necessary where air or gases have to be moved either for rapid combustion or heat transmission.[1] Professor Osborne Reynolds[2] has shown that it is only at low velocities and when unaffected by changes of temperature that water flows in straight stream lines parallel with the axis of the pipe. What he has called the "critical" velocity for any pipe, or the point at which the water ceases to flow in straight stream lines, is given by the expression:—

$$V_c = \frac{1}{278}\frac{P}{D}$$

where D = the diameter of the pipe in metres,
T = the temperature of the water,
$P = (1 + \cdot 0336T + \cdot 000221T^2)^{-1}$
V_c = the critical velocity in metres per second.

Mr. Stanton[3] observed that in a pipe of 1·39 centimetres diameter the critical velocity in centimetres per second was found at about 28·6 as maximum.

The results of Mr. Stanton's experiments showed that the heat transmitted from metal (copper) to water was nearly proportional to the velocity of the water; but these experiments were carried out with small pipes and with small temperature differences, and hence do not afford very certain information for our special subject. The highest velocity experimented with seems to have been 186 centimetres per second, but in those on the effect of variation of velocity, the values of v used were 69, 98, and 123·2 centimetres.

There are several collateral actions connected with the circulation of water in boilers, upon which forced or mechanical circulation must exert a very decided influence. These are priming, delayed ebullition, and the heating of the feed water.

Priming.—As to priming, whatever may be the special conditions of the water, or of the boiler surfaces, which favour frothing of the water, there is no doubt that the boilers which, from their design, cause the projection of considerable quantities of water

[1] See Chap. IV. more fully on this point.
[2] Phil. Trans., 1884, pp. 935–982.
[3] Phil. Trans., A., 1897, Vol. cxc., pp. 67–88.

into the steam space, must be very liable to the presence of priming water in the steam which they deliver. Consequently if we could by suitable arrangements diminish this action, the chances of obtaining dry steam would be greatly increased. The use of forced circulation, combined with causing the currents of water and of hot gases to travel in opposite directions, for the carrying out of which it furnishes the means, attains the desired end by ensuring that the formation of steam takes place when it can escape at once into the steam space, encumbered by only the minimum of water. In boilers which have an upward current of water in the tubes, the maximum amount of steam formation takes place at their upper ends, so that the steam does not, as in other boilers, force along with it a large volume of water up through the whole length of the tubes.

In the boilers arranged for a downward current of water the method of exposing the water to heat in films makes it certain that the steam can escape at once without carrying a large quantity of water with it. Nevertheless, the point at which saturated steam becomes perfectly dry and enters the condition of steam gas is difficult to reach, so that it is more than likely that all steam not actually superheated by direct transmission of heat carries with it more or less vapour in a finely attenuated condition. Some experiments by Professor Osborne Reynolds[1] with a "wire-drawing calorimeter" apparently prove this and raise a doubt as to whether the steam tables calculated from Regnault's experiments, made presumably with dry saturated steam, are correct. The wire-drawing calorimeter is one form of ingenious apparatus which has been devised for obtaining a measure of the percentage of moisture in steam. Since the methods proposed by Hirn and Joule, in which the steam was weighed, either separately or mixed with a known weight of water, various steam calorimeters have been devised and are used in all steam boiler trials which are carried to any notable degree of accuracy. Of these the principal instruments are those of Barrus, Carpenter, Rateau and Peabody.[2]

[1] On "The Dryness of Steam," etc. Manchester Literary and Philos. Soc., 1896.

[2] See Professor Unwin on "Determining the Dryness of Steam," Brit. Assoc. Reports, and Proc. Inst. Mech. Eng., January, 1895.

Delayed Ebullition.—The phenomena of delayed ebullition and of superheating the water in steam boilers, although rare, are recognised as of possible occurrence with water from which the air has been removed by boiling, and which is also free from floating or other impurities.[1] But as almost entire quiescence is a necessary condition to the production of the phenomena, it is apparent that the continued movement of the water by mechanical means must prevent any such actions taking place.

Heating Feed-Water.—Heating the feed-water is also made the more certain and easy by forced circulation, whether the feed-heaters are arranged to work with the waste heat from furnace gases, or, as many prefer, to be heated by steam taken from the exhaust or from some other point.

There are in fact four different methods of heating the feed-water, viz., (1) heating by the waste gases from the furnace, as in Green's and other "Economisers" on land; Mr. E. Kemp's "Compound boiler" (referred to in Chap. IV.), the Belleville, Yarrow and other arrangements for marine boilers; (2) heating by exhaust steam, common to all old forms of injection condensers and now used for feed-heating alone in the forms used by Bailey, Wheeler, Babcock and Wilcox and others; (3) heating by steam after it has been partially used or expanded, as in such arrangements as Weir's, and others; and (4) heating by "live" steam, as in the feed-heaters of Caird and Rayner, Babcock and Wilcox, Kirkaldy, Row and others. There is also another plan, that of Morrison's feed-water heater, in which steam from an evaporator is admitted to and condenses amongst the feed-water. This is apparently an indirect method of utilising the heat of live steam. The live steam is used first to evaporate sea water, and some of the heat is recovered from the steam thus formed and is transmitted to the feed-water.

It is, of course, plain that the utilisation of heat which would otherwise go to waste, as in plans 1 and 2, must be an economy; but economy has also resulted from the use of plans 3 and 4, although the source of it does not lie so distinctly on the surface. There seems, however, little reason to doubt that the explanation

[1] See the *Engineer*, November 26th, 1875, pp. 377–378; Prof. R. H. Thurston, "Manual of Boilers," pp. 268, 269; Hirsch, "Annales des Mines," Vol. v., p. 171.

of the improved results obtained with these classes of feed-heaters is to be found in the fact that an increased speed of circulation of water in the boiler has resulted from their use,[1] causing the transmission of heat from the hot gases to be carried farther than would otherwise have been the case. If so, this is an additional argument in favour of forced or accelerated circulation.

Conditions to be Reached.—In the discussion of a paper on "Water-tube Boilers" by Mr. George Halliday, Wh. Sch. in Trans. Inst. Marine Engineers (April and May, 1898), Vol. x., p. 76, the author of this work observed that "the best results will probably be reached in the future when we have ascertained the best rates of movement of the water on the one side and of the fire gases on the other, for given differences of temperature. Means will have to be introduced also for eliminating the various losses or uncertainties which belong to the combustion department of the boiler as at present arranged. And it is probable that, in order to obtain the best results in this department, a distinct development of combustion under high pressure will be found necessary. All this may issue in the production of a completely new type of boiler."

In the following June, Professor Perry, when discussing Mr. Halliday's paper on "Transmission of Heat through Plates from Hot Gases to Water" (Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xlii., p. 52), expressed a similar opinion. He said, "One small tube conveying hot gases, dragged through at an enormous velocity, and concentric tube conveying water in the opposite direction at great velocity. They had in that combination a method of giving up heat which was fifty times as great as what occurred in an equal amount of heating surface in the best existing boilers. That led to the result that the boiler of the future would burn its fuel under pressure in a very non-conducting chamber, and the products of complete combustion would pass with great velocity through very fine, very thin tubes surrounded with water, which was made to circulate with great rapidity driven by a pump or injector."

In the main these views agree, though it is probable that

[1] See the *Mechanical Engineer*, Vol. i., pp. 424–246 ; vol. ii. pp. 784–786.

Professor Perry's arrangement of gases inside and water outside will not give so good a result as the reverse of that arrangement should give. The gases must pass over the heating surface in enormously larger volume than the water; and as they must necessarily escape at a comparatively high temperature, it is evident that they should form the atmosphere which envelops the water-tube, so that no heat can be radiated away from the hot water surface. But both are agreed in the conclusion that the water should be circulated by mechanical means over the surface in process of its being caused to receive heat transmitted from the gases, and, moreover, that the currents of water and of gas should be made to travel in opposite directions.

Since the foregoing chapter was written some experiments have been carried out by Mr. G. Halliday on the influence of velocity on evaporation in tubes, the results of which are interesting and apparently contradictory, though the experiments are a long way from being exhaustive enough to warrant a general conclusion being drawn from them.

The first set of experiments was published in the *Engineer* on 12th May, 1899, and the second set on 29th December, 1899, both having been first communicated to the Institute of Marine Engineers[1]. The first experiments showed that up to a certain point, when the source of heat was kept constant, and the difference in temperature between the out-flowing hot and the in-flowing cold water was about 150° Faht., the number of thermal units absorbed by the water per minute increased steadily with the speed of flow. This effect was not much altered when the water was heated up to boiling point, but the *rate* of absorption was less at boiling point than at 10 degrees below it.

The apparatus then used consisted of a vertical glass tube with a spiral tube of small diameter placed inside of it and sealed into it at each end. Water from a cistern was allowed to flow through the spiral from below, passing a thermometer placed at each end of the spiral, and flowing from the top end into a graduated measure. The space surrounding the

[1] See Trans. Inst. Marine Engineers, Vol. xi., 84th paper; also "Science Abstracts," Vol. for 1900, pp. 267-268.

spiral was kept full of steam at atmospheric pressure, superheated by being passed through a copper coil heated in a Bunsen flame. With this apparatus there seemed to be a critical point in the velocity beyond which the thermal absorption fell away, sometimes very rapidly. That, however, was due to the heating powers of the apparatus being too limited to cope with the requirements of the water at the higher velocities employed.

In the later experiments the water, previously heated to boiling point in a tank or cistern, was made to flow upwards through a vertical copper tube, heated throughout its entire length by a Fletcher gas burner. The mixture of steam and water delivered from this copper tube was passed into a separator, from which the water went to a measuring flask, and the steam through a condenser to a graduated measure for the condensed steam. The experiments made with this form of apparatus were undertaken to test the rate of heat transmission with water which is freely giving off steam, and is also made to flow through the heating tube at different velocities, the effects of the presence of steam not having been studied in the former experiments.

Mr. Halliday stated that there appeared to be a maximum rate of evaporation at a certain speed of the water, and that on either side of that point the evaporation diminished, a velocity which gave an evaporation about equal to the quantity not evaporated, *i.e.*, an evaporation of half the quantity of water passing in a given time, seemed to give the best result. This result was independent of the degree of heat applied within the limits of the apparatus used, the curves of results with higher heats having the same form as those of lower heats, but appearing at a higher level in the diagram.

He concluded from these experiments that whilst the quantity of water evaporated depends on the quantity of heat supplied to the tube, and on the velocity of the water through the tube, yet the greater the speed of water through the tubes of a water-tube boiler, beyond a certain point, the less will be the evaporation. This, however, does not necessarily follow, because Mr. Halliday's experiments were too limited in extent to permit of any such general deduction being properly derived from

them. Both the range of temperatures and the velocity of circulation employed by him were restricted, and the conditions of the application of heat to the tube, and of the movement of the water in it, were such that no sound conclusion can be drawn from these experiments which would be applicable to a different set of conditions.

CHAPTER VI.

THE INFLUENCE OF TEMPERATURE ON TENACITY AND DUCTILITY.

IT would appear that a limit to the heating of boilers, and to the pressure and temperature of steam carried in them, is fixed by the effects of elevation of temperature upon the tenacity and ductility of iron and steel—as well as other metals.

Although, in some of the experiments on heat transmission mentioned in Chapter IV., the metal plate, or bottom of the open apparatus in which water was evaporated, reached a red-heat, yet it is certain that in a vessel subject to steam pressure, such results could not have been attained, or, at any rate, would have been accompanied by some danger of explosion or collapse.

The investigation of the subject in a practical way dates from Sir W. (then Mr.) Fairbairn's [1] researches, although some experiments on the ultimate tenacity of iron at high temperatures had been previously made by Baudrimont,[2] Seguin, and by the Franklin Institute. These earlier experiments were conducted on a small scale, without reference to the temporary or permanent elongations of the material, or to the effect of heat on its elasticity and ductility.

Fairbairn's Investigations.—Mr. Fairbairn observed no effect on the strength of plate iron up to almost 400° F. At a "scarcely red" heat, the breaking weight of plates was reduced to 16·978 tons from 21 tons at 60° F.; whilst at a "dull-red" it was further reduced to 13·621 tons.

Messieurs Trémery and P. Saint Brice,[3] aided by the celebrated Cagniard Latour, found that at nominally the same temperature *(rouge sombre)* a bar of iron was reduced in strength to one-sixth of its strength when cold. Although this was a greater reduction of strength than Fairbairn observed, yet it must be remembered that, for want of reliable means of measuring

[1] On the Tensile Strength of Wrought Iron at Various Temperature Reports. British Association, 1856, p. 405.

[2] Annales de Chimie et de Physique, 3rd ser. 30, p. 304 (1850).

[3] Annales des Mines, 2nd series, Vol. iii., p. 513.

high temperatures in these days, the estimation of such temperatures was, to a great extent, done by the eye, and a variation in the amount of daylight would cause an apparent difference in the colour observed and therefore in the temperature estimated. "Fairbairn's data would show that the ultimate strength of wrought iron is reduced to about one-half, but M. Tréméry's result explains the generally instantaneous collapse of flues when made red-hot," although their factor of safety may originally have been six.

"A most important question," wrote Mr. F. A. Paget in 1865, "is the effect of temperatures, whether high or low, on the elasticity of the material—whether iron will take a permanent set with greater facility at a high temperature. These data are really more important than those on the ultimate strength, as they would show the influence of temperature on the elastic limit. Here again is a vacancy in existing knowledge, which can scarcely be said to be filled up by the few experiments of the late M. Wertheim[1] on very small wires.

"*Wertheim's Experiment.*—He found, however, that the elasticity of small steel and iron wire increases from 15° C. to 100° C., but at 200° it is not merely less than at 100°, but sometimes even less than at the ordinary temperature.

"As Wertheim used in his experiments wire which according to his statement had a diameter of only from 0·1 to 0·5 line, he was but little exposed to error in respect of its curvature; but on the other hand, he was unable accurately to measure its sectional area, except by calculating the mean area from the specific gravity. As the wires were only about 2·5 feet long between the points where the elastic elongations were measured, and as these measurements were obtained by means of a cathetometer, the values of the modulus of elasticity calculated by him from his experiments on traction not unfrequently varied for the same iron and steel wire to the extent of 10 per cent. and upwards.

"The modulus of elasticity may certainly be more accurately obtained by flexion than by traction, as the amount of deflection may be considerably greater, and therefore more accurately measured than the elastic elongation by tension. But supposing that the value of the modulus of elasticity thus obtained is an

[1] Comptes Rendus, Vol. xix., p. 231.

exact measure of the elastic force on stretching, it is assumed that this force is equal to the elastic force on compression, whilst, according to Hodgkinson, the latter for iron is about $\frac{5}{6}$ of the former ; and, also, that by different strains in different directions, and by the change of form in the sectional area which occurs on flexure, other forces are developed or the conditions are otherwise so changed that the calculations on the common formula become, as some authors affirm, uncertain. Wertheim in one case obtained the modulus of elasticity for steel wire more than 20 per cent. higher by means of transverse vibration than by traction.

Kupffer's Experiments.—"Kupffer's[1] determinations of the modulus of elasticity by flexion and transverse vibrations agree very well *among themselves ;* but although the amount of deflection was determined in his experiments with great accuracy by affixing mirrors to the ends of the sample-bars and measuring the inclination which these mirrors assumed in different positions of the bars, yet his results may be affected by errors amounting to at least $1\frac{1}{2}$ per cent., as his bars had a thickness of only 0·8 to 1·7 line. The third power of this thickness enters into the formula for calculating the modulus of elasticity by flexion, and therefore an error in measurement of 0·00058 inch, which for the thinner bars is more than $\frac{1}{2}$ per cent. of their thickness, causes an error of upwards of $1\frac{1}{2}$ per cent. in the modulus. That an error of measurement of this magnitude was committed may be seen by comparing the thickness measured with that calculated from the specific gravity."

"There is another very important point with respect to wrought iron which has scarcely received the attention it deserves. As would appear from a number of phenomena, there seems to be a sort of thermal elastic limit with iron. When heated, and when its consequent dilatation of volume does not exceed that which corresponds to (perhaps) boiling point, it returns to its original dimensions. Beyond a certain temperature it does not contract again to its pristine volume, but takes a permanent dilatation in consequence, apparently, of its elastic limits having been exceeded. A number of observers have determined the fact with cast iron, and though wrought iron has not been expressly investigated in this direction, there is no doubt that it

[1] Recherches Experimentales sur l'elasticité des Metaux, etc., par. A. J. Kupffer. St. Petersburg, 1850.

exhibits a similar behaviour. Thus,[1] a number of years ago an Austrian engineer, named C. Kolm, remarked that a boiler about 12 metres long and 1·57 metre in diameter, with a thickness of plate of 0·011, permanently expanded at a temperature corresponding to a steam pressure of 5 atmospheres (153° C.) by 0·07193, and did not, when cold, return to its original dimensions. The same thing has been noticed, by means of very accurate measurements, with other boilers.

"A number of experiments by Lieut.-Col. H. Clerk,[2] of Woolwich, on wrought-iron cylinders and plates, bear distinct evidence of a dilatation of volume in wrought iron when repeatedly heated and suddenly cooled."

These facts show that such tests or experiments as those described by the late Mr. W. Parker[3] (in Trans. Inst. N. A., Vol. xxvi., p. 253) and by Mr. John Scott, C.B. (*ibid.*, Vol. xxx., p. 285), must be incomplete as showing what precise strains iron or steel is subject to under conditions of actual work.

A considerable amount of research has been carried out in some of these directions since the date of Mr. Paget's paper, but there is still room for further investigation in connection with the latter questions raised by him.

Fairbairn's Results.—Mr. Fairbairn's experimental results on the tensile strength of boiler plate and of rivet iron at different temperatures are given in the following Tables :—

TABLE LI.

Temperature in degrees Faht.	Breaking Strains.			
	In the direction of the fibre.		Across the fibre.	
	Per sq. inch in lbs.	Per sq. inch in tons.	Per sq. inch in lbs	Per sq. in. in tons.
0	49,009	21·88	——	——
60	50,219	22·41	41,881	18·69
114	41,356	18 46	44,160	19·71
212	44,717	19·96	45,680	20·39
270	44,020	19·65	——	——
340	49,968	22·31	42,088	18·79
395	46,086	20·57	——	——
Red heat	——	——	34,272	15·30

[1] Percy's "Metallurgy," Vol. Iron and Steel (1864), p. 872.

[2] Proceedings of the Royal Society, March 5, 1863.

[3] See also Trans. Inst. N. A., Vol. xix., pp. 178, 179.

In the above instances the plates experimented on were Staffordshire wrought-iron boiler plates of ordinary quality. In the following Table are results of experiments on the tensile strength of rivet or bar iron at a greater range of temperature than the above.

TABLE LII.

Temperature in degrees Faht.	Mean Breaking Weight.	
	Per square inch, in lbs.	Per square inch, in tons.
−30	63,239	28·26
60	62,816	28·05
114	70,845	31·61
212	79,271	35·39
250 to 270	82,636	36·89
310 to 325	84,046	37·52
415 to 435	83,943	37·47
Red heat.	35,000	15·62

"The maximum strength of rivet iron appears to be attained at a temperature of 320° F. This is above the temperature at which the maximum strength of plates was attained, but little or no alteration of strength is observable in plates, whilst that of bars is increased nearly one-half. The iron was of good quality, made from carefully selected scrap iron."

Knut Styffe's Results.—Very careful and complete experiments on tensile strength and elasticity at different temperatures were carried out with both iron and steel by Professor Knut Styffe, Director of the Royal Technological Institute at Stockholm, and an excellent translation into English of his record of the work was made by Mr. C. P. Sandberg.[1] The experiments at high temperature were carried out by means of special apparatus, the heating of the specimens being accomplished by the use of melted paraffin, to temperatures ranging between 212° and 392° F.

Fracture at High and Low Temperatures.—The results of all his experiments on fracture at high and low temperatures are collected in the following Table, regarding which Professor Knut Styffe remarked :—

[1] The Elasticity, Extensibility, and Tensile Strength of Iron and Steel. By Knut Styffe. Translated from the Swedish by C. P. Sandberg. London : John Murray, Albemarle Street. 1869.

TABLE LIII.—RESULTS of EXPERIMENTS on the TENSILE

All the bars tested were filed in the middle to smaller

Those bars preceded by a bracket { were

No. of experiment.	Description of Steel or Iron.	Sample bars. Carbon.	Phosphorus.	Section of the bar where it was not filed. Form.	Diameter or side.	Mean area of the section where filed.
		per cent.	per cent.		inches	sq. in.
{ 1	Bessemer steel from Högbo, marked 1·0	1·14	0·018	Round	0·465	0·1115
2	" " "	"	"	"	"	0·0935
{ 3[2]	" " "	—	—	"	"	0·1252
4[2]	" " "	—	—	"	"	0·1261
{ 5	" " marked 0·6	0·68	—	"	"	0·1135
6	" " "	"	—	"	"	0·1203
{ 7[2]	Bessemer iron from Högbo, marked 0·3	0·33	—	Square	0·348	0·0543
8[2]	" " "	"	—	"	"	0·0811
{ 9	" " "	"	—	Round	0·465	0·1069
10	" " "	"	—	"	"	0·1045
{ 11	Bessemer steel from Carlsdal, marked 0·4	0·42	—	Square	"	0·1883
12	" " "	"	—	"	"	0·1883
{ 13	Uchatius steel from Wikmanshyttan, hardness No. 0·2	1·78	—	Round	"	0·1042
14	" " "	"	—	"	"	0·1042
15	" " "	"	—	"	"	0·1091
{ 16	" " hardness No. 3...	0·69	—	"	"	0·1014
17	" " "	"	—	"	"	0·0968
{ 18	Cast steel from Krupp, marked with one crown ...	0·62	0·02	"	"	0·1299
19	" ...	"	"	"	"	0·1261
{ 20	" " ...	"	"	"	"	0·1187
21	" " ...	"	"	"	"	0·1141
{ 22	Puddled steel from Surahammar, marked N.P. 1 ...	0·8	—	Square	"	0·1956
23	" " "	"	—	"	"	0·1957
{ 24	" " marked N.H 1 ...	0·7	—	Round	"	0·1233
25	" " "	"	—	"	"	0·1195
{ 26	" " marked B.2	0·55	—	"	"	0·1145
27	" " "	"	—	"	"	0·1180
{ 28	" " marked N.P. 3 ...	—	—	"	"	0·1252
29	" " "	—	—	"	"	0·1203
{ 30	English pulled from Low Moor	0·21	0·068	"	"	0·1348
31	" "	"	"	"	"	0·1380
{ 32	" "	"	"	"	"	0·1348
33	" "	"	"	"	"	0·1241
{ 34	" "	"	"	"	"	0·1952
35	" "	"	"	"	"	0·1234
{ 36	" "	"	"	"	"	0·1256
37	" "	"	"	"	"	0·1343

1 Compare

2 Nos. 3, 4, 7, and 8 did not form part of those ordered

STRENGTH OF IRON AND STEEL AT DIFFERENT TEMPERATURES

dimensions for a length of from 4 to 6 inches.

originally parts of the same bar.

Breaking weight per sq. inch of the original mean area of the filed part of the bar.		Area of fracture.	Ratio between the area of fracture and the original sectional area of the filed part.	Elongation by rupture.		Specific gravity determined after the experiment.			Temperature of the bar during the experiments.	The bar broken in
				Excluding the inch where the fracture took place.	On a length of 5·2 inches, the place of fracture included.[1]	Of the part not filed.	Of the filed part.	Difference between the specific gravities.		
lbs.	tons.	sq. in.		per cent.	per cent.				Fahr.	
140,945	62·92	0·1115	1·00	4·0	4·0	7·8508	7·8491	0·0017	+ 53	Water.
137,034	61·17	0·0747	0·80	3·5	4·3	—	—	—	+330	Paraffin.
115,078	51·37	0·0985	0·79	4·0	5·1	—	—	—	+ 55	Air.
131,032	58·49	0·1137	0·90	5·0	5·5	—	—	—	+356	Paraffin.
126,044	56·27	0·0878	0·77	7·0	8·8	—	—	—	− 40	Alcohol.
123,653	55·20	0·0914	0·76	5·9	8·6	—	—	—	+ 59	Water.
66,286	29·59	0·0148	0·27	5·5	9.4	—	—	—	+ 50	Ditto.
77,677	34·67	0·0344	0·42	5·5	9·2	—	—	—	+350	Paraffin.
77,482	34·59	0·0313	0·29	2·8	8·0	—	—	—	+ 60	Water.
76,422	34·11	0·0389	0·37	6·4	10·3	7·8804	7·8781	0·0023	+320	Paraffin
76,991	34·37	0·1257	0·67	19·3	21·2	—	—	—	+ 5	Alcohol.
74,589	33·29	0·1299	0·69	15·3	18·1	—	—	—	+ 60	Water.
141,768	63·28	0·1041	1·00	3·3	3·7	—	—	—	− 29	Alcohol.
132,916	59·33	0·1042	1·00	3·1	—	—	—	—	+ 59	Air.
138,818	61·97	0·1060	9·97	2·4	3·9	—	—	—	+282	Paraffin.
114,526	51·12	0·0795	0·78	12·9	—	—	—	—	+ 53	Water.
116,173	51·86	0·0747	0·77	7·5	9·5	7·8431	7·8263	0·0168	+302	Paraffin.
93,666	41·81	0·0731	0·56	7·7	11·5	7·8473	7·8463	0·0010	− 23	Alcohol.
95,793	42·76	0·0878	0·70	1·00	—	7·8465	7·8292	0·0173	+ 57	Water.
95,519	42·63	0·0653	0·55	12·2	15·9	—	—	—	− 20	Alcohol.
93,666	41·81	0·0699	0·61	6·7	11·0	7·8435	7·8389	0·0046	+ 50	Water.
123,172	54·98	0·1875	0·96	8·0	—	—	—	—	− 29	Alcohol.
118,300	52·81	0·1656	0·85	10·1	11·5	—	—	—	+ 60	Water.
102,518	45·76	0·0949	0·77	12·7	15·0	7·7783	7·7361	0·0422	+ 55	Ditto.
93,254	41·63	0·1003	0·84	6·8	—	7·7830	7·7600	0·0230	+300	Paraffin.
95,724	42·73	0·1003	0·88	9·3	10·4	—	—	—	− 13	Alcohol
89,754	43·06	0·0896	0·76	9·7	11·1	—	—	—	+ 57	Water.
73,492	32·80	0·0796	0·63	17·6	21·3	—	—	—	+ 59	Ditto.
70,266	31·35	0·0699	0·58	7·0	9·9	—	—	—	+311	Paraffin.
61,277	27·35	0·0666	0·49	28·8	30·7	—	—	—	− 32	Alcohol.
56,474	25·21	0·0654	0·47	19·0	23·1	—	—	—	+ 68	Water.
64,091	28·61	9·0639	0·47	20·4	24·9	—	—	—	− 36	Alcohol.
65,189	29·10	0·0567	0·46	18·9	24·4	—	—	—	+ 59	Water.
64,159	28·64	0·0596	0·50	7.25	10·7	7·7981	7·7456	0·0525	+311	Air.
65,394	29·19	0·0667	0·54	8·25	11·5	—	—	—	+320	Paraffin.
59,081	26·37	0·0624	0·50	15·4	19·4	7·7985	7·7425	0·0460	+ 60	Water.
66.355	29·62	0·0715	0·53	8·75	11·8	7·7930	7·7284	0·0646	+323	Paraffin.

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direct from Högbo, but were purchased in Stockholm.

TABLE LIII. *continued.*—RESULTS of EXPERIMENTS on the TENSILE

All the bars tested were filed in the middle to smaller

Those bars preceded by a bracket { were

No. of experiment.	Description of Steel or Iron.	Sample Bars. Carbon.	Sample Bars. Phosphorus.	Section of the bar where it was not filed. Form.	Section of the bar where it was not filed. Diameter or side.	Mean area of the section where filed.
		per cent.	per cent.		inches.	sq. in.
38	English puddled iron from Low M or	0·21	0·068	Round.	0·465	0·0823
39	" "	"	"	"	"	0·0807
40	" "	"	"	"	"	0·1062
41	" "	"	"	"	"	0·0784
42	from Middlesbrough-on-Tees ...	0·07	0·25	"	0·581	0·1909
43	" "	"	"	"	"	0·1815
44	" "	"	"	"	"	0·1933
45	" "	"	"	"	"	0·1881
46	" "	"	"	"	"	0·1880
47	" "	"	"	"	"	0·1990
48	" "	"	"	"	"	0·1946
49	" "	"	"	"	"	0·1913
50	Puddled iron from Motala (Sweden)	0·2	0·02	"	0·465	0·11 0
51	" "	"	"	"	"	0·1214
52	" "	"	"	"	"	0·1069
53	" "	"	"	"	"	0·1210
54	" "	"	"	"	"	0·1176
55	" "	"	"	"	"	0·1196
56	" "	"	"	"	"	0·1188
57	" "	"	"	"	"	0·1207
58	" "	"	"	"	"	0·1145
59	" from Surahammar, N.P.	—	—	"	"	0·1169
60	" "	—	—	"	"	0·1039
61	" "	—	—	"	"	0·1135
62	Iron made in the charcoal hearth from Ayrd (Sweden)	0·07 to 0·18	0·26	Square.	"	0·1810
63	" "	"	"	"	"	0·1819
64	" "	"	"	"	"	0·1373
65	" "	"	"	"	"	0·1373
66	" "	"	"	"	"	0·1341
67	" "	"	"	"	"	0·1326
68	Iron made in the Lancashire hearth from Lesjöforss (Sweden)	0·06	0·022	"	"	0·1845
69	" "	"	"	"	"	0·1800
70	" "	0·07	"	"	"	0·1633
71	" "	"	"	"	"	0·1613
72[2]	" "	"	"	"	"	0·1303
73[2]	" "	"	"	"	"	0·1199

[1] Compare

[2] Nos. 72 and 73 were taken from the previously broken bar, No. 41 in Table IV., which

STRENGTH of Iron and Steel at DIFFERENT TEMPERATURES.

dimensions for a length of from 4 to 6 inches.

originally parts of the same bar.

Breaking weight per sq. inch of the original mean area of the filed part of the bar.		Area of fracture.	Ratio between the area of fracture and the original sectional area of the filed part.	Elongation by rupture.		Specific gravity determined after the experiment.			Temperature of the bar uring the experiments.	The bar broken in.
				Excluding the inch where the fracture took place.	On a length of 5·2 inches, the place of fracture included.[1]	Of the part not filed.	Of the filed part.	Difference between the specific gravities.		
lbs.	tons.	sq. in.		per cent.	per cent.				Fahr.	
57,366	25·60	0·0401	0·49	23·5	23·8	—	—	—	+ 53	Water.
65,394	29·19	0·0425	0·53	9·0	11·8	7·7833	7·7142	0·0691	+275	Paraffin.
60,316	26·92	0·0567	0·53	20·0	24·2	7·7878	7·7404	0·0474	+ 55	Water.
67,316	30·05	0·0462	0·59	11·5	13·2	7·7889	7·7671	0·0218	+280	Paraffin.
61,483	27·44	0·1177	0·62	24·7	29·2	—	—	—	− 40	Alcohol.
57,846	25·81	0·1060	0·58	19·6	23·9	—	—	—	+ 57	Water.
63,885	28·60	0·1177	0·61	23·1	26·8	—	—	—	− 27	Alcohol.
59,287	26·46	0·1257	0·67	20·8	24·5	—	—	—	+ 59	Water.
52,837	23·58	0·1341	0·71	9·7	12·2	7·6808	7·6033	0·0775	+ 60	Ditto
55,010	24·60	0·1099	0·55	20·8	24·1	7·6782	7·4807	0·1975	+ 62	Ditto.
69,717	31·12	0·1216	0·62	14·5	17·0	7·6885	7.5646	0·1239	+318	Paraffin.
62,556	27·92	—	—	8·8	10·6	7·6780	7·5629	0·1151	+419	Ditto.
54,141	24·17	0·0513	0·45	21·5	25·8	—	—	—	− 16	Alcohol.
51·121	22·82	0·0626	0·53	16·3	20·8	—	—	—	+ 60	Water.
63,336	28·27	0·0747	0·71	8·1	—	—	—	—	+320	Paraffin.
68,414	30·54	0·0762	0·63	15·7	17·5	—	—	—	+392	Ditto.
68,482	30·57	0·0580	0·49	21·3	24·3	—	—	—	− 27	Alcohol.
50,367	22·48	0·0667	0.56	11·0	—	7·7177	7·6921	0·0256	+ 53	Water.
53,111	23·71	0·0609	0·51	16·3	19·1	7·7359	7·7091	0·0267	+ 60	Ditto.
65,394	29·19	0·0715	0·59	9·6	—	7.7159	7·7065	0·0094	+347	Air.
63,119	28·21	0·0624	0·55	8·0	—	7·7294	7·7032	0·0262	+374	Ditto.
50,710	22·63	0·0654	0·56	16·8	18·5	—	—	—	− 24	Alcohol.
46,310	20·67	0·0413	0·40	11·2	15·2	7·7918	7·7105	0·0813	+ 53	Water.
57,160	25·51	0·0540	0·48	9·7	13·1	7·7762	7·7458	0·0304	+338	Air.
64,159	28·64	0·1257	0·69	18·7	29·9	7.7424	7·6699	0·0725	+ 55	Water.
79,667	35·56	0·1257	0·69	15·7	—	7·7657	7·7114	0·0543	+302	Paraffin.
66,286	29·59	0·0914	0·66	17·3	20·4	—	—	—	− 16	Alcohol.
67,590	30·17	0·1099	0·80	20·9	21·5	—	—	—	− 11	Ditto.
63,130	28·18	0·0654	0·49	14·25	19·5	—	—	—	+ 55	Water.
73,560	32·83	0·0684	0·52	16·5	20·2	—	—	—	+275	Paraffin.
55,376	24·71	0·0684	0·37	22·5	31·6	—	—	—	− 27	Alcohol.
51,053	22·79	0·0624	0·35	27·7	—	—	—	—	+ 60	Water.
44,328	19·78	0·0401	0·25	25·4	33·1	7·8457	7·8135	0·0322	+ 57	Ditto.
62,169	27·79	0·0624	0·39	15·1	20·2	7·8381	7·8339	0·0042	+314	Paraffin.
56,199	25·08	0·0527	0·41	10·7	17·2	—	—	—	+ 55	Water.
62,718	28·00	0·0596	0·49	8·0	11·3	—	—	—	+330	Paraffin.

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accounts for the breaking-load being greater than for the other bars of the same kind of iron,

"In this Table we have given, as a measure of extensibility, the percentage elongation after fracture, calculated partly on the measured and divided portion of the bar at which fracture did not occur, and partly on the entire length of the divided portion, if the bar was not ruptured beyond the outer divisions. . . .

"From this Table it is seen that among all the bars broken at very low temperatures only one, viz., the cast steel bar No. 18, broke with a smaller load than was necessary to fracture another portion of the same bar at the ordinary temperature. In this case, however, the difference between the two breaking weights is too insignificant to demand attention, and, moreover, an opposite result was obtained with another bar of the same make, No. 20. In general, the extensibility has not been found less at low than at ordinary temperatures. On the contrary, at higher temperatures, between 212° and 392° F., the absolute strength of iron is considerably greater than at ordinary temperatures, as Dr. Fairbairn also found in his experiments; but, on the other hand, the extensibility appears to be somewhat diminished. In steel, however, there does not seem to be any essential difference, either in absolute strength or in extensibility within the range of temperature mentioned.

"The greatest increase of strength by elevation of temperature was found in those kinds of iron which contained but little carbon; and in order to ascertain that this result was not accidentally occasioned by the filed portions of the bars having been harder than the rest, we determined the amount of carbon at the place of fracture in the bar numbered 71 in Table LIII., this bar having been ruptured in a paraffin bath. The proportion of carbon in that part was found to be 0·07 per cent., and therefore was not greater than in other bars of the same kind of iron. From this experiment, as well as from those performed in hot air with the cast iron apparatus, it is manifest that the increased strength exhibited by iron at high temperatures cannot be referable to any chemical influence or carbonisation exerted by the paraffin on the iron during the experiment.

Effect on Specific Gravity.—"As it is well known that the specific gravity of iron is diminished by stretching at ordinary temperatures, we considered it would be of interest to determine whether

the same effect is produced, and, if so, in what manner, when the traction is performed at other temperatures. For this purpose we have taken the specific gravities of some of the bars mentioned in Table LIII., after fracture, examining both the filed portion and the original unfiled part, which in general has not suffered any perceptible alteration by stretching. It was believed that from these determinations some explanation might possibly be found of the very remarkable quality which iron possesses of becoming stronger at certain degrees of heat than at ordinary temperatures. As seen, however, from Table LIII., there is generally no great difference between the diminutions of specific gravity when the fracture by extension was performed at different degrees of temperature."

Effect on Modulus of Elasticity.—Tables LIV. and LV., which follow, show the results of experiments made to determine "in what manner the position of the limit of elasticity, and the value of the modulus of elasticity in iron and steel, are dependent on the temperature at which tension is performed."

The apparatus used, and the precautions to ensure accuracy which were adopted, are, as in all cases, fully described by Professor Knut Styffe, but to follow these his book must be referred to.

The following are some extracts of general importance :—

"The position of the limit of elasticity in iron and steel is in a great measure dependent on the mechanical treatment to which the material has been subjected and on the temperature to which it has been subsequently exposed. This limit can never, therefore, be known with accuracy without a special determination, and by such a determination the limit itself is raised. It has been found that with a bar which has been extended beyond its limit of elasticity the position of the new limit might, *under ordinary conditions*, be easily determined by representing the permanent elongations graphically ; for the upper parts of the curves for a new series of experiments at the same temperature will lie in the continuation of the preceding curves. It was therefore supposed, at the commencement of these experiments, that by taking advantage of this circumstance it would be possible to determine with sufficient accuracy the dependence of the limit of elasticity on the temperature at which the extension was performed. For such a purpose, therefore, the limit of

TABLE LIV.—RESULTS OF EXPERIMENTS to ascertain in what

affected by the TEMPERATURE at

The bars tested were each about six feet long, and filed in the

No. of bar	Description of steel or iron.	Treatment of the bars immediately before they were tested.	Amount of carbon. In the bar tested.	Amount of carbon. In bars of the same kind.
			per cent.	per cent.
	Hammered Bessemer steel from Högbo, marked 1·2 :—			
1	1st experiment ...	Heated to slight redness and slowly cooled...	—	1·35
,,	Same bar ... 2nd ,, ...	Heated ½ hour in paraffin at 266° Fahr.	—	,,
,,	,, ... 3rd ,, ...	Do. do. do.	—	,,
,,	,, ... 4th ,, ...	... ...	—	,,
,,	,, ... 5th ,, ...	... ...	—	,,
,,	,, ... 6th ,, ...	Do. do. 284°F.	—	,,
,,	,, ... 7th ,, ...	Heated for 2 hours in paraffin at 275° Fahr.	—	,,
,,	,, ... 8th ,, ...	... ...	—	,,
,,	,, ... 9th ,, ...	Heated and slowly cooled	—	,,
,,	,, ... 10th ,, ...	... ...	—	,,
,,	,, ... 11th ,, ...	... ...	—	,,
	Hammered Bessemer steel from Högbo, marked with the old No. 3·5 :—			
2[1]	1st experiment ...	... ...	1·26	—
,,	Same bar ... 2nd ,, ...	... ...	,,	—
,,	,, ... 3rd ,, ...	... ...	,,	—
,,	,, ... 4th ,, ...	... ...	,,	—
,,	,, ... 5th ,, ...	Heated to slight redness and slowly cooled...	,,	—
,,	,, ... 6th ,, ...	Cooled for ½ hour at 9° Fahr.	,,	—
,,	,, ... 7th ,, ...	... ...	,,	—
,,	,, ... 8th ,, ...	... ...	,,	—
	Hammered Bessemer steel from Högbo, marked 0 9 :—			
3	1st experiment ...	... ...	—	1·05
,,	Same bar ... 2nd ,, ...	... ...	—	,,
,,	,, ... 3rd ,, ...	... ...	—	,,
,,	,, ... 4th ,, ...	Slightly heated and slowly cooled ...	—	,,
,,	,, ... 5th ,, ...	... ...	—	,,
	Rolled puddled steel from Surahammar, marked B 1 :—			
4	1st experiment ...	... ...	0·66	—
,,	Same bar ... 2nd ,, ...	... ...	,,	—
,,	,, ... 3rd ,, ...	... ...	,,	—
,,	,, ... 4th ,, ...	... ...	,,	—
,,	,, ... 5th ,, ...	... ...	,,	—
,,	,, ... 6th ,, ...	... ...	,,	—
	Rolled puddled steel from Surahammar, marked N 1 :—			
5	1st experiment ...	... ...	0·56	—
,,	Same bar ... 2nd ,, ...	... ...	,,	—
,,	,, ... 3rd ,, ...	... ...	,,	—
,,	,, ... 4th ,, ...	... ...	,,	—

[1] The bar No. 2 was not filed in the middle, but

[2] This bar had been previously used for other experiments, and

degree the LIMIT of ELASTICITY on Stretching Iron or Steel is

which the Extension is performed.

middle for a length of about four and a half feet. (See p. 106).

The original section as to		The filed middle part as to		Average temperature during the experiment.	Difference between the average temperature during the experiment and the previous temperature.	Limits of elasticity.				Elongation of the middle filed part of the bar during each experiment.
Form.	Diameter or side.	Length.	Sectional area.			Calculated according to the previous experiments.	Found to be.	Consequently. Higher.	Consequently. Lower.	
	inch.	feet.	sq. inch.	Fahr.	Fahr.	lbs. per sq. in.	lbs. per sq. in.	lbs. per sq. in.	lbs. per sq. in.	per cent.
Round.	0·488	4·50	0·1679	+ 62	—	—	61,414	—	—	0·367
,,	,,	,,	,,	+ 68	+ 6	74,109	81,657	7,548	—	0·060
,,	,,	,,	,,	+ 55	− 3	82,481	82,481	0	0	0·081
,,	,,	,,	,,	+264	+109	83,510	79,256	—	4,254	0·027
,,	,,	,,	,,	+ 62	−102	79,873	78,226	—	1,647	0·521
,,	,,	,,	,,	+ 62	0	78,913	76,991	—	1,992	0·065
,,	,,	,,	,,	+266	+204	78,569	91,607	13,038	—	0·030
,,	,,	,,	,,	+ 57	−209	92,842	96,960	4,118	—	0·047
,,	,,	,,	,,	+ 64	—	—	61,758	—	—	0·104
,,	,,	,,	,,	− 2	− 66	72,188	79,736	7,548	—	0·092
,,	,,	,,	,,	+ 55	+ 57	82,344	69,992	—	12,352	0·105
Square.	0·372	5[1]	0·1015[1]	+ 64	—	—	67,833	—	—	0·150
,,	,,	,,	,,	+249	+185	71,158	68,414	—	2,744	0·367
,,	,,	,,	,,	+ 55	−194	70,404	76,579	6,175	—	0·099
,,	,,	,,	,,	+278	+223	77,540	73,766	—	3,774	0·201
,,	,,	,,	,,	+ 59	—	—	65,189	—	—	0·143
,,	,,	,,	,,	+ 46	− 13	66,561	66,561	0	0	0·113
,,	,,	,,	,,	− 11	− 57	67,933	70,678	2,745	—	0·085
,,	,,	,,	,,	+ 50	+ 39	71,364	67,590	—	3,774	0·171
Round.	0·465	4·62	0·1156	+ 57	—	—	64,502	—	—	0.130
,,	,,	,,	,,	− 22	− 79	69,306	72,737	3,431	—	0·126
,,	,,	,,	,,	+ 59	+ 81	—	69,649	—	—	0·204
,,	,,	,,	,,	+269	+210	75,825	85,431	9,606	—	0·171
,,	,,	,,	,,	+ 60	−209	88,176	90,921	2,745	—	0.762
Round.	0·5	4·37	0·1214	+ 57	—	—	46,318	—	—	0·110
,,	,,	,,	,,	− 22	− 79	50,435	53,180	2,745	—	0·187
,,	,,	,,	,,	+ 51	+ 73	57,983	55,239	—	2,744	0·289
,,	,,	,,	,,	+266	+215	62,444	62,444	0	0	0·320
,,	,,	,,	,,	+ 53	−213	68,620	70,335	1,715	—	0·241
,,	,,	,,	,,	+264	+211	72,737	71,364	—	1,363	0·307
Square.	0·476	4·49	0·1561	+ 59	—	—	39,113	—	—	0·303
,,	,,	,,	,,	+275	+216	43,573	46,318	2,745	—	0·324
,,	,,	,,	,,	+ 53	−222	53,043	55,444	2,401	—	0·318
,,	,,	,,	,,	− 27	− 80	56,611	59,013	2,402	—	0·396

was of the same thickness throughout the five feet.
thereby elongated, which accounts for the high limit of elasticity.

TABLE LIV. *continued.*—RESULTS of EXPERIMENTS to ascertain in affected by the TEMPERATURE at

The bars tested were each about six feet long, and filed in

No of bar.	Description of Steel or Iron.	Treatment of the bars immediately before they were tested.	Amount of carbon. In the bar tested.	Amount of carbon. In bars of the same kind.
			per cent.	per cent.
	Rolled puddled steel from Surahammar, marked N P 2 :—			
6[2]	1st experiment ...	... ...	—	0·7
,,	Same bar ... 2nd ,, ...	Heated for ½ hour in paraffin at 284° Fahr.	—	,,
,,	,, ... 3rd ,, ...	Do, do. at 302° Fahr....	—	,,
,,	,, ... 4th ,, ...	Heated for 25 minutes in paraffin at 266° Fahr.	—	,,
,,	,, ... 5th ,, ...	... ...	—	,,
,,	,, ... 6th ,, ...	... ...	—	,,
	Rolled puddled iron from Low Moor :—			
7[2]	1st experiment ...	... ...	—	0·2
,,	Same bar ... 2nd ,, ...	... ...	—	,,
,,	,, ... 3rd ,, ...	... ...	—	,,
	Rolled puddled iron from Motala (Sweden) :—			
8	1st experiment ...	... ...	—	0·2
,,	Same bar ... 2nd ,, ...	... ...	—	,,
,,	,, ... 3rd ,, ...	... ...	—	,,
,	,, ... 4th ,, ...	... ...	—	,,
	Rolled puddled iron from Motala (Sweden) :—			
9[2]	1st experiment ...	... ...	—	0·2
,,	Same bar ... 2nd ,, ...	... ...	—	,,
,,	,, ... 3rd ,, ...	... ...	—	,,
,,	,, ... 4th ,, ...	... ...	—	,,
,,	,, ... 5th ,, ...	... ...	—	,,
,,	,, ... 6th ,, ...	Heated to redness and slowly cooled	—	,,
,,	,, ... 7th ,, ...	Heated for ½ hour in paraffin at 284° Fahr.	—	,,
,,	,, ... 8th ,, ...	... ...	—	,,
,,	,, ... 9th ,, ...	... ...	—	,,
,,	,, ... 10th ,, ...	Heated for ½ hour in paraffin at 284° Fahr.	—	,,
,,	,, ... 11th ,, ...	... ...	—	,,
,,	,, ... 12th ,, ...	... ...	—	,,
	Rolled puddled iron from Surahammar, marked N H :—			
10	1st experiment ...	... ...	—	0·2
,,	Same bar ... 2nd ,, ...	... ...	—	,,
,,	,, ... 3rd ,, ...	... ...	—	,,
	Rolled iron made in charcoal-hearth at Ayrd (Sweden) :—			
11	1st experiment ...	... ...	—	0·1
,,	Same bar ... 2nd ,, ...	... ...	—	,,
,,	,, ... 3rd ,, ...	... ...	—	,,

[2] This bar had been previously used for other experiments

what degree the LIMIT of ELASTICITY on Stretching Iron or Steel is

which the Extension is performed.

the middle for a length of about four and a half feet.

The original section as to		The filed middle part as to		Average temperature during the experiment.	Difference between the average temperature during the experiment and the previous temperature.	Limit of elasticity.				Elongation of the middle filed part of the bar during each experiment.
Form.	Diameter or side.	Length.	Sectional area.			Calculated according to the previous experiments.	Found to be.	Consequently. Higher.	Consequently. Lower.	
	inch.	feet.	sq. inch.	Fahr.	Fahr.	lbs. per sq. in.	lbs. per sq. in.	lbs. per sq. in.	lbs. per sq. in.	per cent.
Square.	0·488	4·50	0·2163	+ 62	—	—	52,151[2]	—	—	0·106
"	"	"	"	+ 62	0	62,444	68,276	5,832	—	0·044
"	"	"	"	+ 57	− 5	71,776	71,776	0	0	0·048
"	"	"	"	+ 68	+ 11	72,599	72,051	—	548	0·066
"	"	"	"	+237	+169	74,795	68,620	—	6,175	0·079
"	"	"	"	+ 64	−173	69,992	71,707	1,715	—	0·082
Round.	0·5	4·72	0·1256	+298	—	—	41,515[2]	—	—	0·476
"	"	"	"	+ 51	−247	42,201	46,318	4,117	—	0·986
"	"	"	"	− 16	− 67	48,377	50,435	2,058	—	0·179
Round.	0·476	4·65	0·1229	+ 57	—	—	34,172	—	—	0·256
"	"	"	"	+267	+210	36,368	34,035	—	2,333	0·571
"	"	"	"	+ 57	−210	35,339	39,662	4,323	—	0·151
"	"	"	"	+278	+221	40,142	35,339	—	4,803	0·705
Round.	0·476	4·49	0·1112	+284	—	—	34,447[2]	—	—	0·276
"	"	"	"	+ 57	−227	35,819	39,250	3,431	—	0·374
"	"	"	"	+275	+218	39,799	35,270	—	4,529	0·379
"	"	"	"	+ 64	−211	37,260	42,132	4,972	—	0·978
"	"	"	"	− 5	− 69	42,544	45,289	2,745	—	0·230
"	"	"	"	+ 60	—	—	27,448	—	—	0·294
"	"	"	"	+ 64	+ 4	28,134	31,565	3,431	—	0·484
"	"	"	"	+264	+200	33,344	29,369	—	3,975	0·276
"	"	"	"	+ 60	−204	29,918	33,898	3,980	—	0·161
"	"	"	"	+ 64	+ 4	34,653	33,966	—	687	0·093
"	"	"	"	+271	+207	34,653	29,849	—	4,804	0·390
"	"	"	"	+ 66	−195	30,535	34,653	4,118	—	0·935
Round.	0·476	4·50	0·1269	+ 57	—	—	28,134	—	—	0·103
"	"	"	"	− 18	− 75	29,506	32,594	3,088	—	0·256
"	"	"	"	+300	+318	35,956	28,820	—	7,136	0·138
Square.	0·511	4·49	0·2087	+ 53	—	—	45,426	—	—	0·358
"	"	"	"	− 22	− 75	46,455	49,886	3.431	—	0·630
"	"	"	"	+ 50	+ 72	50,092	47,347	—	2,745	0·328

thereby elongated, which accounts for the high limit of elasticity.

TABLE LV.—RESULTS of EXPERIMENTS for DETERMINING the MODULUS

No. of the bar.	Description of Iron or Steel.	Specific gravity of the bar.	Amount of carbon. In the bar tested.	Amount of carbon. In bars of the same kind.	Section as to [1] Form.	Section as to [1] Mean area before the experiment.	When the bar has not been heated.	The bar had just before the modulus was taken obtained a permanent elongation of
			per cent.	per cent.		square inch.	lbs. per square inch.	per cent.
1	Hammered Bessemer steel from Högbo—Marked 1·2	7·832	—	1·35	Round.	0·1823	—	—
2[3]	„ with the old number of hardness 3·5. The bar No. 2 Table LIV.	7·850	1·26	—	Square.	0·1015	30,124,180	0·004
3	„ 0·9. The bar No. 3 in Table LIV.	7·849	—	1·05	Do.	0·1156	30,604,520	0·014
4[3]	Hammered Bessemer iron from Högbo—Marked with the old number of hardness 5	7·878	0·1	—	Do.	0·1003	32,320,020	0·002
5		7·879	0·15	—	Do.	0·1107	34,241,380	0·001
6	Rolled cast-steel from Wikmanshyttam—Degree of hardness No. 1	7·832	1·22	—	Round.	0·1691	31,222,100	0·021
7	Hammered cast-steel from F. Krupp—Marked with two crowns	7·843	—	0·61	Do	0·2065	31,359,340	0·0008
8	Rolled puddled steel from Surahammar—Marked B 1. The bar No. 4 in Table LIV.	7·781	0·66	—	Square.	0·1214	—	—
9	Marked N 1. The bar No. 5 in Table LIV.	7·828	0·56	—	Do.	0·1561	29,918,320	0·027
10	Rolled puddled iron—From Low Moor	7·780	—	0·20	Round.	0·1961	31,976,920	0·006
11	„ Dudley	7·463	—	0·09	Do.	0·1844	28,408,680	0·008
12	„ „	7·444	—	0·09	Do.	0·2006	27,448,000	0·077
13	„ Motala (Sweden)	7·734	0·05	—	Do.	0·1942	30,261,420	0·008
14	„ „ „ The bar No. 8 in Table LIV.	7·734	—	0·2	Square.	0·1229	29,575,220	—
15	From Surahammar, marked N ...	7 789	0·14	—	Do.	0·2176	31,084,860	0·018
16	„ „ „ N H. The bar No. 10 in Table LIV. ...	7·807	—	0·2	Do.	0·1269	30,467,280	0·002
17	Rolled iron made in charcoal-hearth—From Aryd (Sweden). The bar No. 11 in Table LIV.	7·780	—	0·07 to 0·18	Do.	0·2087	26,761,800	0·037
18	„ „ „ „	7·761	—	Do.	Do.	0·2279	27,791,000	0·003
19	Rolled iron made in charcoal-hearth—From Hallstahammar (Sweden) ...	7·829	—	0·07	Do.	0·1891	28,957,640	0·013
20	„ „ „ ...	7·854	—	0·07	Do.	0·1965	30,810,380	0·001

[1] For the bars in Table LIV., which were filed to smaller dimensions in the middle, this table shows
[2] The influence of the permanent elongation on the modulus of elasticity was first examined after the be referred to the value obtained after heating.
[3] The bars Nos. 2, 4, and 5, were not ordered at Högbo, but were purchased in Stockholm.

of ELASTICITY in Iron and Steel by TRACTION.

The Modulus of Elasticity.											
When the bar had been heated to slight redness.	The bar had just before the modulus was taken obtained a permanent elongation of	Diminished by the bar having undergone permanent elongation	The permanent elongation which the bar had obtained shortly before.	Diminution.	By an increase of temperature. From	By an increase of temperature. To	Diminished on an average for an increase of temperature of 1·8°F.=B.	Increase.	By reduction of the temperature. From	By reduction of the temperature. To	Increase on an average for a decrease of temperature of 1·8° F.=B.
lbs. per square inch.	per cent.	per cent.	per cent.	per cent.	Fahr.	Fahr.	per cent.	per cent.	Fahr.	Fahr.	per cent.
31,839,680	0·003	6·42[2]	0·58	—	—	—	—	0·5	+50	− 9	0·015
30,535,900	0·006	4·92[2]	0·66	3·8	+55	+271	0·031	1·0	+48	−22	0·025
31,496,580	0·000	9·24[2]	0·72	—	—	—	—	—	—	—	—
34,584,480	0·017	6·5	0·61	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	8·6	0·7	4·2	+60	+275	0·035	—	—	—	—
32,114,160	0·004	6·2	0·78	3·8	+59	+264	0·033	1·2	+50	−11	0·035
30,330,040	0·015	—	—	—	—	—	—	2·1	+51	−27	0·047
—	—	5·7	0·16	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	6·6	1·77	—	—	—	—	—	—	—	—
30,779,000	0·001	7·76	0·72	—	—	—	—	—	—	—	—
—	—	—	—	5·0	+59	+284	0·040	1·9	+48	−25	0·046
—	—	—	—	—	—	—	—	—	—	—	—
30,741,760	0·003	—	—	—	—	—	—	—	—	—	—
—	—	4·3	0·54	—	—	—	—	2·0	+55	+25	0·044
29,232,120	0·003	0·78	0·32	—	—	—	—	—	—	—	—
—	—	—	—	3·7	+59	+262	0·033	—	—	—	—
30,810,380	0·000	—	—	—	—	—	—	—	—	—	—

only the form and the mean area.
bar had been heated, and hence the percentage diminution of the modulus which is here given should

elasticity should be determined for each bar, first at the ordinary temperature and then at a very low or high temperature ; the curves of elongation for both series should afterwards be traced, and finally that point determined at which the tangent to the upper part of the curve of the latter series cuts the ordinate of the terminal point of the former. The length of that portion of the ordinate lying between the tangent referred to and the end of the preceding curve would thus measure the *temporary* elevation or depression of the limit of elasticity consequent upon the difference of temperature at the two experiments. In this manner we have found that the limit of elasticity in both steel and iron is always higher at low temperatures, and in iron is lower at high temperatures, than when the extension is performed at the ordinary temperature ; but that, on the contrary, in hard steel at a heat of 266° to 302° F., it is sometimes higher and sometimes lower. When the limit of elasticity in such steel has been found higher at about 284° than at about 59° F., and has been again examined at the latter temperature, the result has often been somewhat higher than might have been anticipated from the experiments at high temperatures. (Compare Table LIV., bar No. 1, series 7 and 8, with No. 3, series 4 and 5.) This arose from the fact, afterwards observed, that when a stretched bar is heated, even to so moderate a temperature as 266° or 302° F., a change is effected in the molecular condition of the metal, which is retained after the heat has been removed ; and therefore the limit of elasticity is often *permanently* altered. Since we know that the limit of elasticity is lowered in iron and steel by annealing, after having been previously raised by tension or other mechanical treatment, it was not expected that a moderate heating could raise the limit any further. (Compare Table LIV., bar No. 1, series 2 with No. 6, series 2 and No. 9, series 7.) Sometimes we have even found that the limit of elasticity in stretched bars has been perceptibly raised by merely allowing the bar to remain at rest for several days after stretching. . . . The metal appears to acquire by this means new strength after having suffered from overstraining. On the other hand, it has not been found that by cooling to a very low temperature any perceptible *permanent* influence has been exerted on the position of the limit of elasticity in iron and steel."

"By determining in this manner the limit of elasticity at high temperatures, the temporary influence of the heat has not been ascertained distinct from its permanent influence; and therefore the results attained by the method described above do not—at least for iron—give any trustworthy *measure* of the temporary change in the limit of elasticity by heating. As, however, the subject has been but very little investigated, we have considered that the results are of sufficient importance to merit publication. In Table LIV. we have therefore given the results of the experiments with reference to the position of the limit of elasticity at very low temperatures, as well as those undertaken to determine the *permanent* influence of heating and cooling, Experiments on the limit of elasticity at different temperatures should, however, show, with at least sufficient accuracy for practical purposes, by *how much* the limit is raised in iron and steel when stretched at low temperatures, and *within what limits* it may vary when stretched at higher temperatures not exceeding 302° F."

In experiments on the variation of the modulus of elasticity at different temperatures, Professor Knut Styffe's method was first to determine, by several experiments at ordinary temperatures, the differences between the elastic elongations when the bar was subjected to successive loads, these differences being reduced to an average corrected by a formula given by him. Then similar determinations were made at high or low temperatures and were finally repeated at ordinary temperature.

"If the bar has not been overstretched, either previously or during the experiment, the results of the tension at ordinary temperatures, as performed before and after heating or cooling, have nearly always shown the closest agreement; and we have then taken the average of all these and compared it with the mean result of the experiments at high or low temperature. If E_1 denote the modulus of elasticity at a low or high temperature, and $L_1 - L_0$ the mean value of the corrected difference between the elastic elongations obtained with loads P_1 and P_0; and if E, $L^1 - L$, P^1 and P represent corresponding values by tension at the ordinary temperatures, then we obtain—

$$\frac{E_1}{E} = \frac{L^1 - L}{L_1 - L_0} \cdot \frac{P^1 - P_0}{P_1 - P}$$

or if, as usually happened,

$$P_1 - P_0 = P^1 - P$$

then

$$\frac{E_1}{E} = \frac{L^1 - L}{L_1 - L_0}$$

The ratio $\frac{E_1}{E}$ is thus always independent of the section of the bar; and the accuracy with which it may be determined depends, when the extending force is alike in all the experiments, only on the accuracy with which the differences between the elastic elongations may be measured.

If the bar has been overstretched, either before or during the experiment, or if it has originally been much bent and then straightened when cold, the experiments conducted at ordinary temperatures with the same load, *after* a series of experiments at a higher (and sometimes also after those at a lower) temperature, present less differences between the elastic elongations than are obtained from those which *precede* such a series of experiments. This results from the influence, already alluded to, which any great change of temperature exerts on overstretched bars, an influence which partially restores the elastic force which is lost by overstretching."

Table LV. shows the results of these experiments in a collected form.

Influence on Flexion.—Professor Styffe concluded his investigations by experiments testing the influence of different temperatures on flexion.

"As it was found, from previous experiments, that the modulus of elasticity on tension is nearly alike in steel and iron of the same specific gravity, but that it increases as the temperature falls and diminishes as the temperature rises, it was considered interesting to examine the influence which these conditions would exert on flexion, because the elastic deflections may be much greater than the elastic elongations at tension, and therefore the former admit of measurement with greater accuracy."

"In all experiments referring to the influence of temperature on the modulus of elasticity, the bars were tested first at the ordinary temperature, then at the higher or lower temperature, and finally again under ordinary conditions. If both series of

experiments at the ordinary temperature agree in their results, it is evident that the change of temperature has not *permanently* altered the elastic force of the bar, but that the differences observed between the deflections at a high or a low temperature, and at the ordinary temperature have, therefore, arisen only from the differences in the thermometric conditions during the experiment.

"If E_1 and E_0 denote the values of the modulus of elasticity at two different temperatures t_1 and t_0, and if d_1 and d_0 denote the measured differences of deflection with the same load, and a the linear coefficient of expansion of the material, then we obtain with sufficient accuracy the value of the ratio $\frac{E_1}{E_0}$ thus :—

$$\frac{E_1}{E_0} = \frac{d_0}{d_1}\left\{1 + a\,(t_1 - t_0)\right\}^3 = \frac{d_0}{d_1}\left\{1 + 3a\,(t_1 - t_0)\right\}$$

On the cooling of our apparatus from 59° F. to -4° F., we have found the mean value of $a = 0{\cdot}000013$, and on heating from 59° F. to 266° F., $a = 0{\cdot}00002$.

"The results obtained are given in Table LVI.

"In these calculations no correction has been made for change of dimensions consequent upon change of temperature ; for the measurement of the dimensions is generally taken at temperatures between 32° and 68° F., and the application of the results to particular cases would therefore have been more difficult with this correction. If a comparison be instituted between the influence of temperature on the elastic force at flexion and at traction, or, in other words, between the values of the coefficients β and β_1 given in Tables LV. and LVI., the correction referred to should in strictness be made in both cases, although β is only increased thereby about 0·001 and β_1 0·004."

TABLE LVI.—RESULTS of EXPERIMENTS to determine the

N.B.—All the bars tested had a length of 4·3 feet

No. of experiment.	Description of Iron or Steel.	Specific Gravity of the bar.[1]	Amount of carbon. In the bar tested.	Amount of carbon. In bars of the same kind.	Sectional area of bars not filed. Form.	Sectional area of bars not filed. Diameter or side.	Sectional area of bars filed. Rectangular section. Average width.	Sectional area of bars filed. Rectangular section. Average height.
			per cent.	per cent.		in.	in.	in.
	Hammered Bessemer steel from Högbo—							
1	Marked 1·0	7·868	—	—	—	—	0·48	0·4890
2[2]	Marked with the old No. of hardness 3·5, the bar No. 2 in Table LV. ...	7·850	1·26	—	—	—	0·3097	0·3165
	Hammered Bessemer iron from Högbo—							
3[2]	Marked with the old No. of hardness 5, the bar No. 5 in Table LV.	7·879[3]	0·15	—	—	—	0·3476	0·3473
4	Rolled Bessemer steel from Carlsdal—	—	0·99	—	Square.	0·4651	—	—
	Rolled puddled steel from Surahammar—							
5	Marked N 1, the bar No. 9 in Table LV	7·828	0·56	—	—	—	0·3629	0·4029
6[2]	„ B 1, the bar No. 8 in Table LV.	7·781	0·66	—	—	—	0·3469	0·3474
7	„ P 1	—	—	0·7	Square.	0·4651	—	—
	Rolled puddled iron—							
8	From Low Moor	7·780	—	0·2	Round.	0·5	—	—
9	From Middlesbrough-on-Tees	—	—	0·97	Ditto.	0·6162	—	—
10	The stem of a rail from Cwm Avon in Wales, cut out by a planing machine, and heated and rolled to a bar	7·597	—	—	—	—	0·4523	0·5009
	Rolled puddled iron—							
11[2]	From Motala. The bar No. 14 in Table LV	7·734	—	0·2	—	—	0·3238	0·3251
12	From Surahammar, marked N. The bar No. 15 in Table LV.	7·789	0·14	—	—	—	0·4588	0·4702
13[2]	From Surahammar, marked N H. The bar No. 16 in Table LV.	7·807	—	0·2	—	—	0·3473	0·3483
	Rolled iron made in charcoal-hearth—							
14	From Ayrd. The bar No. 17 in Table LV	7·780	—	0·1	—	—	0·4513	0·4533
15[2]	„ „ 18 „	7·761	—	0·1	—	—	0·4791	0·4690
16	From Hallstahammar. The bar No. 19 Table LV.	7·829	—	0·07	—	—	0·4052	0·4520
17[2]	From Hallstahammar. The bar No. 20 Table LV.	7·854	—	0·07	—	—	0·4263	0·4584

REMARKS.—The bars Nos. 1, 2, and 3 were not ordered from Högbo, but were bought in Stockholm. The bar No. 2, which after annealing gave a modulus of elasticity of 30,535,900 lbs., on stretching was tested by bending in two directions at right angles to each other. The modulus of elasticity was 31,908,300 lbs. in the one case, and 31,565,200 lbs. in the other. The bar was again annealed, but the modulus was not increased to more than 32,388,640 lbs. per sq. in.

[1] The specific gravity was taken when
[2] The bars Nos. 2, 3, 6, 11, 13, 15, and 17, had been
[3] By annealing, the specific gravity

MODULUS of ELASTICITY in Iron and Steel by FLEXION.

each, the distance between the supports being 4 feet.

The modulus of elasticity.												
When the bar had not been heated.	When the bar had been heated.	Decrease by the permanent deflection of the bar.	The permanent deflection which the bar had obtained immediately before.	Decrease through hardening.	Decrease.	By increase in the temperature. From	To	Average diminution by an increase of temperature of 1·8° F. = B_1.	Increase.	By reduction of temperature. From	To	Average increase by reduction of temperature of 1·8° F. = B_1.
lbs. per sq. inch.	lbs. per sq. inch.	per cent.	in.	per cent.	per cent.	Fahr.	Fahr.	per cent.	per cent.	Fahr.	Fahr.	per cent.
30,760,346	—	1·55	0·1476	1·0	1·98	+59	+266	0·017	0·64	+57	0	0·020
—	31,908,300	—	—	—	—	—	—	—	—	—	—	—
—	32,388,640	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	3·2	—	—	—	—	1·12	+57	+2	0·036
29,232,120	30,741,760	—	—	1·1	3·28	+51	+269	0·027	1·44	+57	+2	0·046
—	30,673,140	—	—	—	—	—	—	—	1·20	+59	−2	0·035
—	—	—	—	1·6	2·18	+60	+257	0·020	0·48	+50	+14	0·024
—	—	—	—	—	—	—	—	—	0·95	+66	+9	0·030
—	—	—	—	—	—	—	—	—	1·02	+60	+5	0·033
27,310,160	27,379,380	—	—	—	—	—	—	—	1·33	+66	+5	0·040
—	29,849,700	—	—	—	—	—	—	—	1·14	+66	0	0·031
30,810,380	30,810,380	1·88	0·4476	—	2·60	+57	+273	0·022	0·96	+55	−2	0·030
—	31,839,680	—	—	—	—	—	—	—	0·99	+66	+11	0·032
27,585,240	27,585,240	1·47	0·0813	—	4·06	+57	+260	0·036	1·18	+57	+2	0·038
—	27,516,620	—	—	—	—	—	—	—	—	—	—	—
31,084,860	31,290,720	0·70	0·7034	—	—	—	—	—	1·11	+66	0	0·030
—	30,398,660	—		—	—	—	—	—	—	—	—	—

The bar No. 13 was bent throughout the whole of its length, and straightened again. The modulus of elasticity was thus decreased 6·6 per cent.

The modulus of elasticity of the annealed bar No. 15 on flexion was first 27,379,350 lbs., and by repeated annealing did not increase to more than 27,516,620 lbs. per sq. in.

he bars were in their original state.

eated immediately before the experiments.

vas increased to 7·882.

W. Parker's Experiments.—During the year 1880 a series of tensile tests of English and German steel at various temperatures was carried out under the direction of Mr. Wm. Parker, then chief engineer-surveyor of Lloyd's Registry of Shipping, by whom the results were communicated to the present author.

The results are given in the following Table :—

TABLE LVII.

Temperature. Fahr.	Stress in Tons per square inch.		Elongation per cent.	
	English.	German.	English.	German.
70°	31·5	30·3	18·7	16·7
450°	35·7	39·2	14·5	10·2
610°	32·0	34·4	12·5	13·2
1,000°	13·8	11·7	3·0*	24·2

* Broke close to the end.

In these experiments the tenacity increased as the temperature rose from 70° to 450°, whilst the ductility diminished, but between 450° and 1,000° both rapidly fell away, except in the case of the German steel, which showed, on the contrary, an increase of ductility.

Kollmann's Experiments.—Following these tests, as to date of publication in this country, but rivalling in completeness those of Professor Styffe, there is the series of experiments carried out by Dr. J. Kollmann at the works of the Gutehoffnungshütte, near Oberhausen, the results of which were communicated by him to the Verhandlungen des Vereins zur Beförderung des Gewerbfleisses (1880, p. 92).[1]

Illustrations of the testing machines and test pieces employed will be found in *Engineering* of February 4th, 1881. In all the tests made, only ordinary iron as daily produced and used at the Gutehoffnungshütte was employed, it being the object of the experiments to determine the behaviour of such iron as the Works ordinarily made. Fibrous iron, fine-grained iron, and

[1] An abstract of this paper is published in *Engineering* of Feb. 4, 1881, p. 109. See also Min. Proc. Inst. C. E., Vol. lxxxiv., p. 417.

Bessemer steel were tested, their relative specific gravities being 7·62, 7·69, and 7·84. The test pieces used in the smaller machine were all 13 mm. (0·51 inch) in diameter, or 13 mm. square, and in the larger machine 40 mm. by 10 mm., or 1·58 by 0·39 inch, say 0·6201 square inch. Careful measurements, both before and after the tests, were made by means of micrometers. The following gives the chemical composition of the three qualities used :—

TABLE LVIII.

	Weldable wrought Iron.	Fine grained Iron.	Bessemer Steel.
Carbon	0·10	0·12	0·23
Silicon	0·09	0·11	0·30
Phosphorus	0·34	0·20	0·09
Sulphur	0·03	trace	0·05
Manganese	0·07	0·14	0·86
Copper	0·07	0·06	0·07
Iron	99·30	99·36	98·40
	100·00	99·99	100·00

Special means were adopted for heating the test pieces, and a second test piece of the same quality of iron was always heated along with the one put in the testing machine, so that this second piece should be used for measuring the temperature of each experiment by means of a calorimeter. No correction was considered necessary to allow for any water lost by evaporation during an experiment, or for losses by radiation. The calorimeter was so well protected against radiation that in a trial extending over two hours there was a loss of only 1·1° C., the temperature of the air being 21·2° C.

Experiments were made to determine the rate of cooling of small test pieces 40 mm. by 10 mm. in section, and the results are plotted in the curve in Fig. 123, the horizontal divisions giving the time in minutes, and the vertical ordinates the temperature in degrees C. Similar experiments were made with the larger test pieces, 13 mm. diameter by 280 mm. long, and their curve of decrease of temperature is shown in Fig. 124.

With regard to the regular experiments, a Table was given containing the results of 52 tests, showing the effects of rise of

temperature in reduction of resistance to rupture, and in increase of the contraction of sectional area, as well as increase of extension. On account of the rapidity with which the test pieces cooled it was found impossible to make accurate observations at a higher temperature than 1080° C. (1976° F.), and for this reason Dr. Kollmann recommends that future experiments should be made with test bars of larger diameter, which would retain their heat longer. Taking the initial strength as 37·5 kilos. per square millimetre or 23·81 tons per square inch at 0° C., and calling this breaking load 100, the progressive diminution in resistance to rupture is thus shown :—

TABLE LIX.

Degrees Centigrade.	Fibrous Iron.	Fine Grained Iron.	Mild Bessemer Steel.
0	100	100	100
100	100	100	100
200	95	100	100
300	90	97	94
400	73	—	—
500	38	44	34
600	19	—	—
700	16	23	18
800	11	—	—
900	6	12	9
1,000	4	7	7
2,250	0 Broke without appreciable load	—	—

That is to say, at a temperature of 200° C. the breaking load in the case of the fibrous iron was reduced to 22·6 tons, or 95 per cent. of the initial load ; at 300° C. to 21·4 tons ; at 400° C. to 17·39 tons ; at 500° C. to 9·14 tons ; at 600° C. to 3·94 tons ; at 800° C. to 2·54 tons ; at 1000° C. to 0·05 ton ; whilst at 2250° C. the iron broke without any appreciable load. These results and the corresponding ones with the other two qualities of iron tested are given graphically in the following curves (Figs. 125, 126, 127), the melting temperature of wrought iron being assumed at

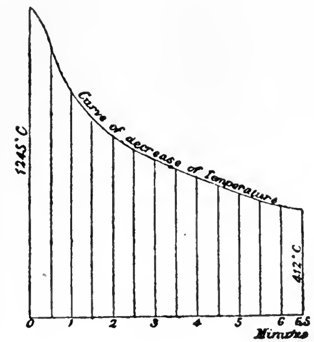


FIG. 123.

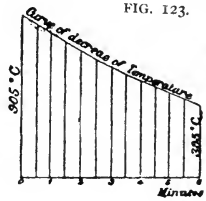


FIG. 124.

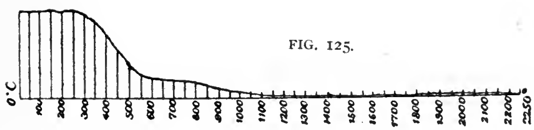


FIG. 125.

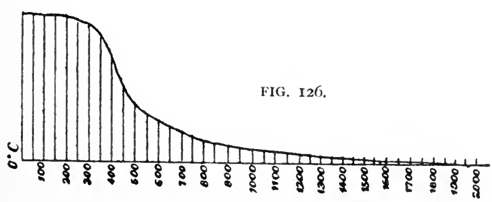


FIG. 126.

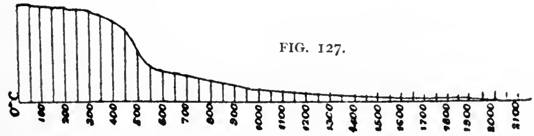


FIG. 127.

2250° C. (4082° F.) according to Dr. Wedding. The results shown by these curves up to about 1100° C. (2012° F.) are fairly accurate, but beyond that temperature it was most difficult to obtain reliable readings. Up to about 450° C. (842° F.) there was an increase in the extension as well as in the reduction of sectional area, which continued in the latter case up to 600° C., whilst the extension decreased. Between 600° C. and 700° C. (1112° and 1292° F.) the contraction decreased, but above 700° C. it increased again. The extension also increased between 700° C. and 850° C. (1292° and 1562° F.), but from this point it very rapidly decreased.

From a number of experiments the elastic limit was determined for 750° C. (1382° F.) to be 2·30 tons per square inch, at 800° C. (1472° F.) 1·27 ton, and at 850° C. (1562° F.) to be 0·95 ton per square inch.

Subsequently some experiments were made with predetermined loads in order to test the reduction of sectional area and the extension at given temperatures. The temperatures ranged between 460° and 700° C. (860° and 1292° F.), the loads at these temperatures respectively being in tons per square inch 2·86 and 2·35. The reductions of sectional area were 7·5 and 40·83 per cent., and the elongations 4·5 and 22 per cent. Figs. 126 and 127 show graphically the results with the other qualities of iron used.

These tests were combined with an investigation of the temperatures at which iron is rolled, and of its behaviour under the action of rolling, in order to obtain a basis for a theory of rolling mills. This investigation, although interesting, has only an indirect application to our subject, inasmuch as it revealed that the strength of bars was to some extent increased by the amount of work and compression to which they were subjected. This, however, has a limit, because the experiments of Pisati and others on the extension of heated iron and steel wire under different loads and at different temperatures from 32° to 572° F. (0° to 300° C.) gave discordant results.

Pisati's Experiments with Wire.—Pisati found that with unannealed wire the extension is very small, and decreases with the rise of temperature. It was observed that, in a wire cooled at a dark red heat, the strength decreased between 57° and 122° F., but increased from that point up to 194°; decreased again up to 248°, remaining then constant up to 392°, and then slowly

decreasing to 455° F., when it suddenly commenced to increase, after which a slow decrease in strength set in. It must be remarked, however, that the strength at 572° was greater than at 57°. The extension decreased between 57° and 167°, and then increased up to 212°, again decreasing rapidly to 257°, when the variation disappeared, and the extensibility remained constant up to 437°. Again it increased quickly, subsequently more slowly until at 572° it was the same as at 57° F. This irregularity was quite absent in the case of Dr. Kollmann's tests of iron and steel plate.

Effect of High Temperature on Steel.—Again, steel being a material capable of being fused, it is found that it cannot be wrought at so high a temperature as that which malleable iron stands without any damage, and that as the temperature of fusion is approached steel suffers in strength and ductility, becoming what is technically termed "burned." It probably forms some union with oxygen such as does Bessemer steel when overblown, because by careful manipulation its good qualities can be to a great extent restored.

Effect of Low Temperature on Steel.—On the other hand it is dangerous to put work upon steel plates or bars at too low a heat, and careful investigations have shown that when worked, by rolling, bending, or hammering, at a blue heat or about 250° F. permanent injury is done to the strength of the material, and internal stresses are set up which have produced the mysterious fractures so puzzling to engineers and shipbuilders in the early days of the introduction of that material in the construction of boilers. The presence of a comparatively high percentage of carbon and a tensile strength of 29 to 32 tons per square inch are factors in the production of the injurious effects of a blue heat, although steel of a less tensile strength, and even wrought iron, may suffer from it. This matter was carefully inquired into in consequence of some trouble with the thick steel plates required for steam boilers of large diameter for high pressures, and full accounts of experiments will be found in Trans. of the Inst. of Naval Architects, Vols. xix., pp. 172–192; xxvi., pp. 253–277; xxvii., pp. 67–150; and Min. Proc. Inst. C. E., Vol. lxxxiv., pp. 114–207; xcviii., 147, etc.[1]

[1] See also Min. Proc. Inst. C. E., Vol. lxix., 35; lx., 219; lxxxviii., 463; Tracts, Folio Vols. 29–32; Proc. Inst. Mechanical Engineers, 1880, p. 225.

Water-tube boilers are to a great extent removed beyond danger from this source, because they are under no necessity to employ thick plates in their construction, and it has been found that the chance of damage to their plates or tubes from the above cause is extremely small.

Professor Martens' Report.—Further investigations were commenced in 1886, under the auspices of two German technical societies, the Verein zur Beförderung des Gewerbfleisses of Berlin and the Verein Deutscher Eisenhüttenleute of Dusseldorf, and were reported upon by Professor Martens[1] in Mittheilungen aus den Königlichen technischen Versuchsanstalten zu Berlin (No. iv., Vol. viii., 1890, page 159). It was considered that previous experiments had not been sufficiently uniform and exhaustive, especially with iron and steel up to a temperature of 600° C., and consequently a systematic series of experiments was decided upon. It was intended to subject to the tests four qualities of mild steel having a tensile strength of 22·86, 26·67, 30·48 and 34·28 tons per square inch in their annealed condition, but the material furnished for the last or fourth group of tests was found to be not up to the required standard, and therefore only three qualities were tested. Carefully formed and annealed test pieces were prepared, and all necessary precautions were taken to have the temperature and other readings correct. Special apparatus was used for both cold and hot tests; in the latter case the test pieces were kept at the required temperature during test by being immersed in melted paraffin, for temperatures up to 200°, or in melted alloys of lead and tin, or of lead only, for temperatures up to 600° C.

A description of the testing machine was published in the Zeitschrift des Vereins deutscher Ingenieure, 1886, p. 171, and Mittheilungen aus den Technischen Versuchsanstalten of 1889, Supplementary No. iii.

"In ordinary tests with the machine employed for these experiments no measurements are taken between the moment when the maximum load is reached and the final fracture. In the present case, however, it was thought desirable to observe more accurately the phenomena occurring between maximum load and fracture, since it was evident beforehand that at

[1] See abstract in Min. Proc. Inst. C.E. Vol. civ. 209–224.

different temperatures very considerable differences in the behaviour of the metal during this period would show themselves.

"For observing the decreasing tensile strength of a test piece the automatic recorder on the left side of the testing machine was employed. The course of the experiment was generally as follows: The test piece, after accurate measurement of all

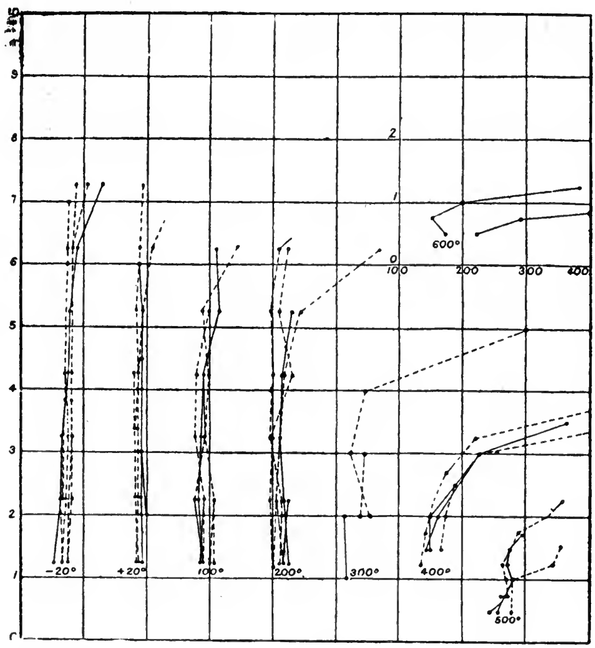


FIG. 128.

parts, was pushed from below into the furnace, and a tight joint made by means of the conical shoulder smeared with fine clay; the test piece and furnace were then firmly connected by a nut. The iron tube (filled with nitrogen) of the air thermometer was next placed inside the furnace, the measuring rods of the mirror apparatus were attached, and finally the stirring mechanism and cover. After the test piece had been fixed in the spherical bearings of the testing machine, the mirror apparatus was connected."

All the pieces to be tested at high temperatures were previously tested several times at an ordinary temperature as to their elastic extension within the limits of proportionality, so that the extension for one ton (*i.e.*, a metric tonne = 0·9842 ton avoirdupois) could be determined with great accuracy and from this the modulus of elasticity. After these preliminary observations the gas-jet was lighted and the furnace gradually heated. The material for filling the inner space of the furnace was

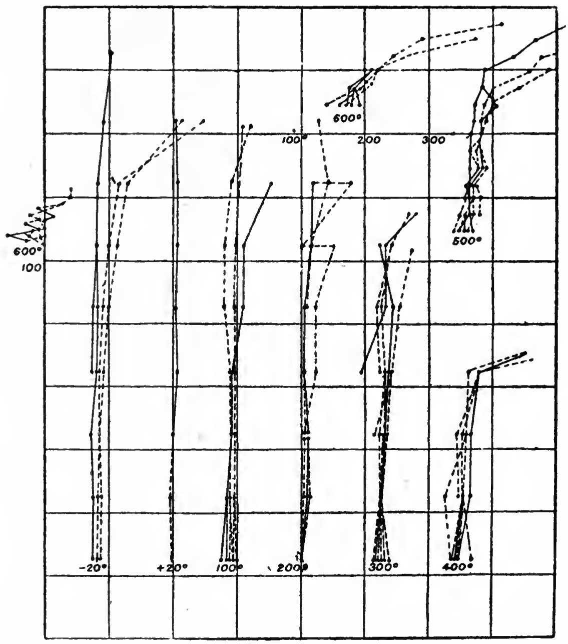


FIG. 129.

melted and poured in when the furnace was sufficiently hot. The temperatures up to 400° C. were observed by means of a mercury thermometer, and the higher temperatures with an air thermometer. At 450° the results obtained from both thermometers were compared and graphically recorded—special precautions being taken to neutralise the variations of the air thermometers.

"The main results are given in a tabular form in the original paper, but for comparison are also graphically represented. In

Figs. 128, 129, and 130, the extension differences, corresponding to the various loads, are shown for the different qualities of metal, I., II., and III., and the various temperatures. These diagrams allow an opinion to be formed of the degree of accuracy obtained, and also on the question as to how far the material can be credited with a proportional extension. From the decreasing length of the parallel portions of the curve-groups with increasing temperatures, the lowering of the limit of proportionality is plainly visible

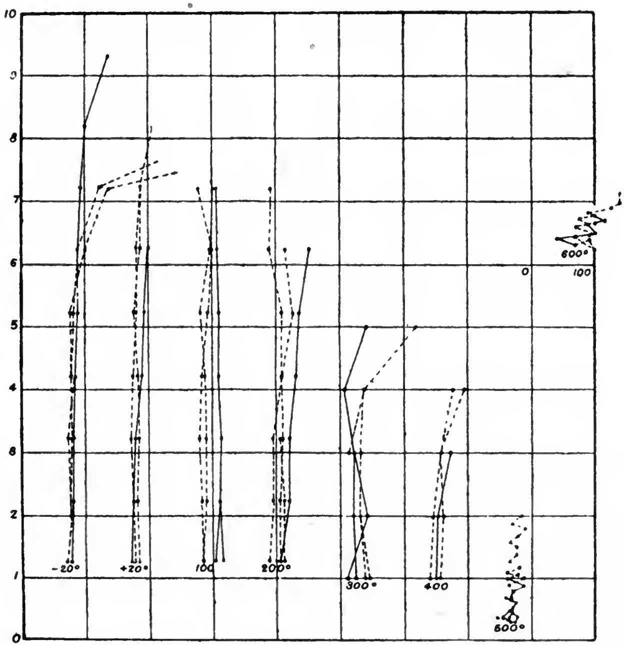


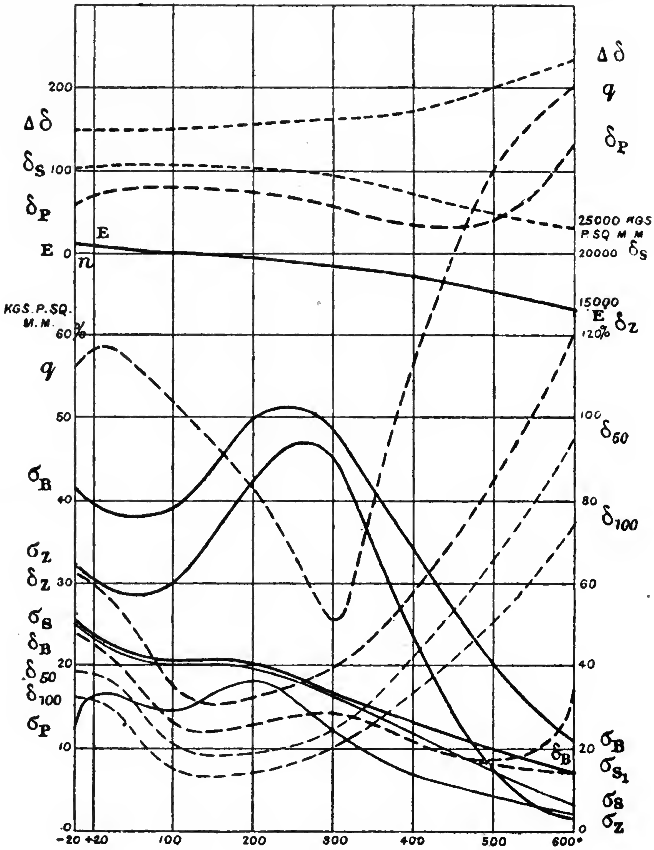
FIG. 130.

Even at 300° it appears questionable whether the test pieces can be truly said to show any proportional extension.

In Figs. 131, 132, and 133, the chief results are delineated for the three qualities of material. The quantity represented by each curve is denoted by the letters at the commencement of each on the left hand, the meaning of the notation being as follows :—

$\Delta\delta$=Percentage of elongation per ton of load.

δ_s=Percentage of elongation per limit of stretch, or limit of elasticity, *i e.*, yielding point where flow of metal commences.



QUALITY I.

FIG. 131.

δ_P=Percentage of elongation per limit of proportionality, or the point up to which stress and strain, accurately measured, remain proportional.

E=Modulus of elasticity.

q=Contraction of area in per cent.

σ_B=Maximum stress.

δ_Z=Breaking stress.

δ_Z=Percentage of elongation at fracture.

σ_S=Stress at limit of stretch.

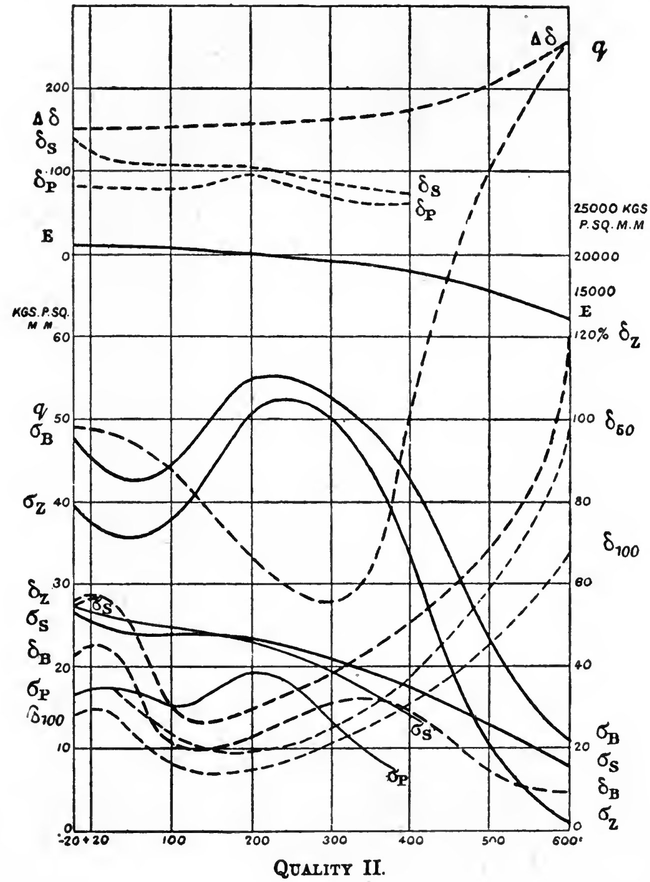


FIG. 132.

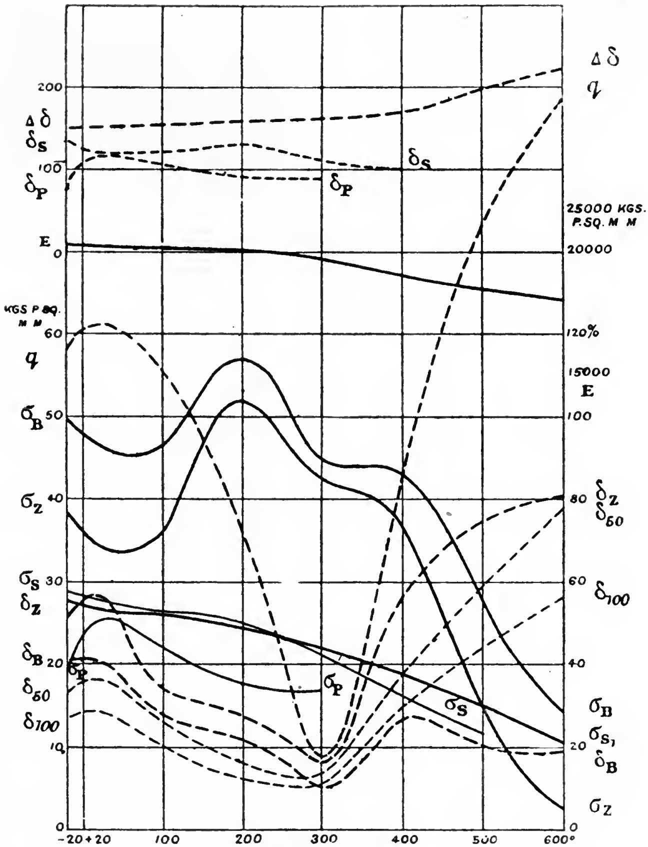
δ_B=Percentage of elongation at maximum load.

σ_P=Stress at limit of proportionality.

δ_{100}=Percentage of elongation in 200 millimetres.

The elongations, except where otherwise stated, are referred to the test length of 206 millimetres.

Figs. 131 to 133 show very clearly how the stresses σ_B and σ_Z decrease considerably from $-20°$ up to about $50°$, and after that rapidly increase until they attain a maximum at from $200°$ to $250°$. This maximum value is for all the qualities of material



QUALITY III.

FIG. 133.

tested considerably in excess of the value for $+20^{\circ}$, and by the following amounts :—

Quality.		Excess for σ_B.		Excess for σ_Z.
I.	...	34 per cent.	...	62 per cent.
II.	...	27 ,, ,,	...	45 ,, ,,
III.	...	25 ,, ,,	...	50 ,, ,,

The curves for σ_Z follow a similar course. On comparing the curves for σ_B and σ_Z, it will be found that the maxima and minima occur at nearly the same temperatures. The following

are the ratios of σ_Z to σ_B in per cent. for various temperatures, as calculated from the mean values obtained :—

TABLE LX.

Quality of Material.	Ratio for							
	$-20°$	$+20°$	100°	200°	300°	400°	500°	600°
I.	76	75	77	86	96	66	39	12
II.	85	82	85	92	96	76	43	7
III.	7	74	79	91	96	84	49	16

With the exception of some of the test pieces of quality III. the material which is strongest in a cool state remains so when heated.

The diagrams (Figs. 134 and 135) allow a comparison of the leading results for all three qualities of material tested.

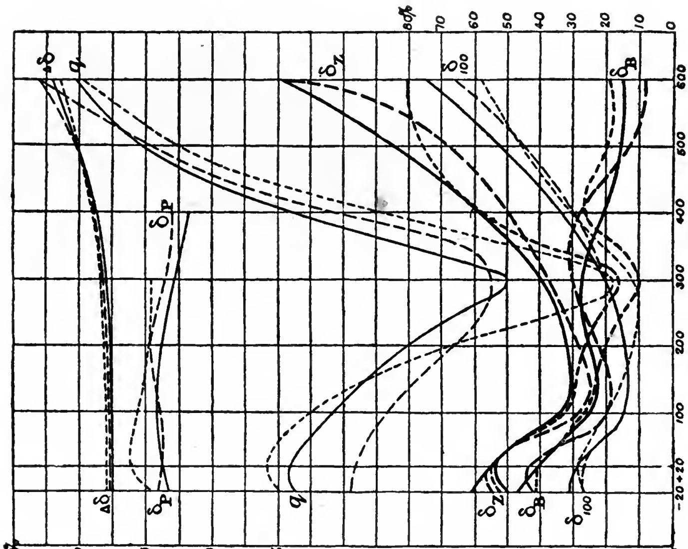
In general No. III. exhibits the same characteristics, as regards the values of σ_B and σ_Z, as the other two, but deviates notably from the latter at 300°. The elongation δ_B increases between $-20°$ and $+20°$, and then for I. and II. decreases and reaches a minimum at about 130°. From this point the curves rise again up to between 280° and 330°, and then fall.

For No. III. the minimum value of δ_B is reached only at 300°, and the curve afterwards rises, a maximum occurring at 400°. Similar differences are also to be observed in the character of the curves for δ_Z.

The following Table, compiled from the mean observed values, gives the ratios in per cent. of δ_B to δ_Z, for various temperatures :—

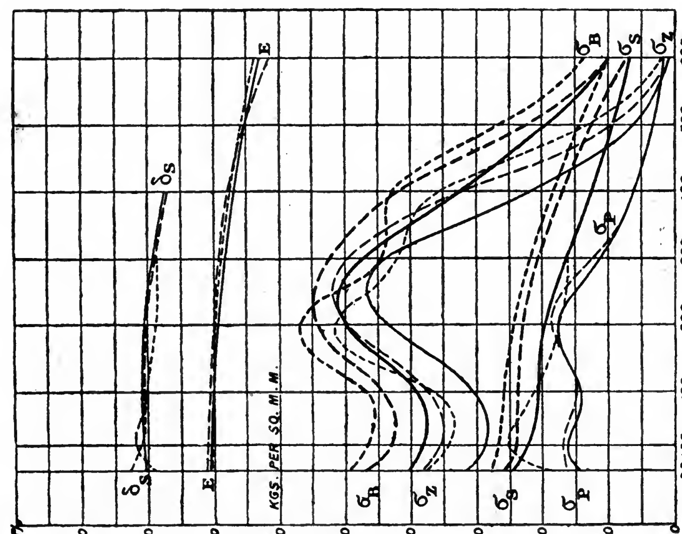
TABLE LXI.

Quality of Material.	Ratio for							
	$-20°$	$+20°$	100°	200°	300°	400°	500°	600°
I.	78	76	76	79	73	36	20	[28]
II.	75	79	68	76	81	58	19	8
III.	78	72	81	74	59	48	26	15



LEADING RESULTS FOR QUALITIES I—III.

FIG. 135.



LEADING RESULTS FOR QUALITIES I—III.

FIG. 134.

In Fig. 136 the stress diagrams for material of quality No. II. are reproduced. The limit of stretch in each diagram is denoted by S, the point of maximum stress by B, the point of fracture by Z. At 400° the material assumed the character of the soft metals, such as zinc. The irregularities at the points *a* and *b* occurred when the flow extended to the shoulders of the test pieces, beyond the actual test length.

The variations in the contraction of area were extraordinarily great. For all three qualities the smallest value of q, the reduction of area, occurs at 300°.

The stress at the limit of proportionality increases with rising temperature between $-20°$ and $+20°$, reaching a maximum about $+20°$; it then falls slightly to 100°, and at 200° attains a second higher maximum, subsequently falling rapidly. The elongation at the limit of proportionality δ_P, is subject to no

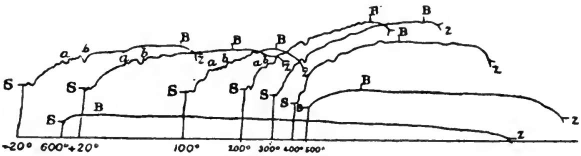


FIG. 136.

appreciable alterations. For the stresses usual at ordinary temperatures the engineer may therefore reckon, in steel heated even up to 200°, on elongations proportional to the load and on sufficient safety. It would, however, scarcely be safe to draw conclusions from the results of these experiments as to the admissible working stress for temperatures above 200°, or for frequent changes of temperature ranging from 150° to 350°. Reliable values in such cases could only be arrived at by repeated tests, continued for long periods, with the metal in a heated state.

The question of the safety of iron structures may be influenced by the peculiar behaviour of the material at 300°. At this temperature the strength is greater, but the reduction of area and elongation are less than in a cold state. Fracture occurs suddenly without previous contraction, the metal exhibiting a certain brittleness, which also finds expression in the appearance

of the fractured surface. On this account it is questionable whether at 300° steel is capable of resisting repeated shocks."

A further series of experiments on wrought iron, mild steel, copper, delta-metal, and manganese bronze, by M. Rudeloff, is reported in the same paper[1] which had previously published M. Martens' results, but these experiments do not call for special notice.

Whilst, however, wrought iron, Siemens steel, copper, and delta-metal all proved to be comparatively or wholly unsafe under stresses at temperatures above 250° C., manganese bronze proved to be very little affected by heat, so that it could be safely used at 250° C.

M. Rudeloff also carried out experiments at the Imperial Navy Yard, Wilhelmshaven, on the strength of iron and steel at low temperatures, but these do not specially bear upon our subject.

Professor Carpenter's Tests.—Professor Carpenter[2] has, however, recently carried out, at Sibley College, Cornell University, tests on the effects of both decrease and increase of temperature on tensile strength and has carried the latter to a higher point than usual.

The general results show first a decided increase in strength, accompanied by a corresponding rise in the strength at elastic limit, as the temperature is lowered—the latter, however, not being so well marked. The percentage of elongation remains essentially constant and so does the modulus of elasticity at all temperatures from + 70° to − 60° F.—the range of the tests. Some previous tests on wrought iron and steel at high temperatures showed a decided increase in strength as the temperature increased from 70° to about 500° F., after which the strength rapidly diminished. A combination of these experiments would seem to show that the strength of wrought iron increases with the change in temperature from about 70° F. in either direction, and that the change is well marked, of considerable amount, and is characteristic of all specimens.

[1] Mittheilungen aus den Königlichen Versuchsanstalten zu Berlin, 1893, p. 292; see also Stahl und Eisen, 1890, p. 607; Min. Proc. Inst. C.E., Vol. cxvii., p. 461.

[2] Published in the issue for 1898 of "The Technic," by the University of Michigan Engineering Society. See also the *Railroad Gazette* and the *Mechanical Engineer*, November 26th, 1898.

Fig. 137 is a combined diagram showing the results of the tests made both at low and at high temperatures. In plotting this diagram, the strength in both series of tests was equalised to a common starting point at 70° F. so as to make the curve

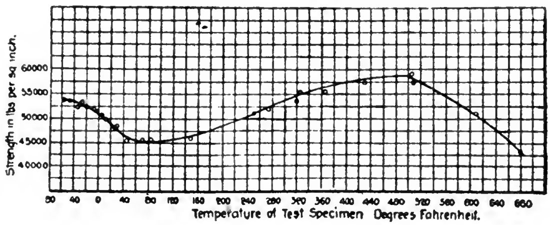


FIG. 137.

continuous. This in result may not be true, but the strict record would only show the curve of strength for the higher temperatures in a position slightly above the one shown. The material in both series of tests was as nearly uniform as possible, although some years intervened between the two series. The material tested at high temperatures was slightly stronger than that used in the low-temperature tests.

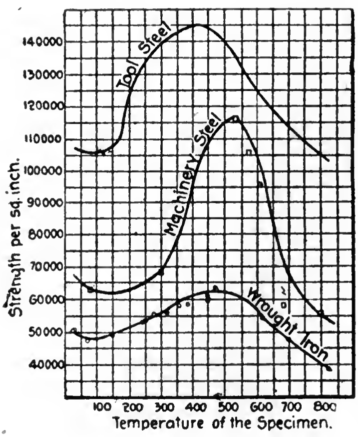


FIG. 138.

In Fig. 138 are given the curves of tests of wrought iron, machinery steel, and tool steel, at high temperatures. The similarity of the form of the curves for different materials shows, so far as the points of maximum and minimum indicate, that the nature of the material has little effect on the general character of the relation of strength to change of temperature, and, further, that the strength is greatly affected by the temperature.

Fig. 139 shows the elongation in specimens eight inches in

length of wrought iron and tool steel at different temperatures. The elongation decreases at first with rise of temperature until a minimum is reached at about 250° F., after which it increases with the temperature.

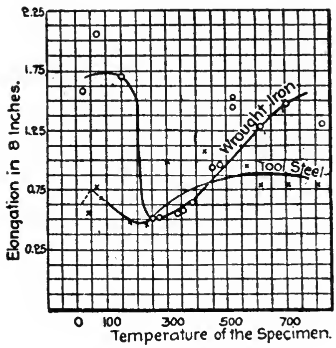
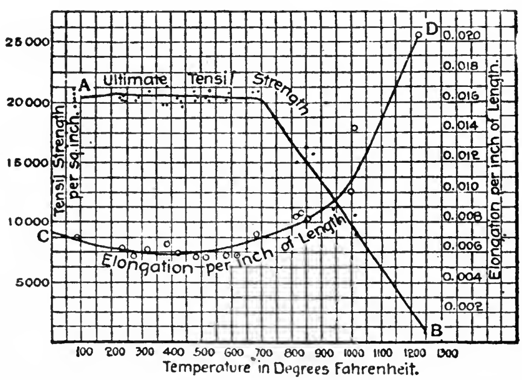


FIG. 139.

An interesting comparison of the results with cast iron is afforded by Fig. 140, which gives the results of tests with that material. The tensile strength of cast iron remained practically uniform from a temperature of 70° to nearly 700° F., but from that point it decreased in rapid proportion to the increase of temperature, becoming practically *nil* at 1240° F. The elongation per inch in length appeared to decrease slightly from 100° to 400°, after which it increased with rise of temperature to 1200°. The elongation of cast iron is so small under the best conditions that it has little importance beyond that belonging to scientific



Effect of Temperature on Strength of Cast Iron.

FIG. 140.

interest. The tests, however, indicate a brittle condition at about 300° or 400° F.

Professor Carpenter discussed the question of the production

of crystalline fractures, and both his report and that of Professor Martens (already alluded to) should be consulted for details of that branch of the inquiry. The more recondite side of the investigation into the molecular changes in iron and steel at high temperatures will be found in the writings of Barrett (Phil. Magazine, Vol. xlvi., p. 472), Pionchon, and Le Chatelier (Comptes Rendus de l'Academie des Sciences, Vol. cii., pp. 670, 1454), and Osmond (Comptes Rendus, vol. ciii., p. 743).[1]

Strength of Copper and Alloys.—Investigations into the effects of high temperatures on the strength of copper and of various alloys have also been made ; and as many of these materials may be used for boiler fittings or accessory apparatus, the results have more or less connection with our subject.

We have seen that at the temperature corresponding to a steam pressure of 200 lbs. per square inch, viz., about 388° F. or 215° C., the strength of wrought iron or steel is not much affected, and in fact that it increases till some point between 350° and 540° F. is reached. At the same time the ductility has decreased, and if the metal is steel which has been worked at a blue heat, there might be serious consequences. Apart from that both wrought iron and steel should be reliable at even the highest of these temperatures. "With copper and its alloys," we are informed, "a very different state of affairs obtains. The steam pipes which proved perfectly reliable with steam of 80 lbs. pressure and a temperature of, say, 324° F., have proved much less satisfactory when this pressure has been doubled, though this has involved an increase in the temperature of only about 37° F. Careful laboratory experiments have conclusively established the fact that, under certain conditions, copper may suffer a serious loss of strength on being baked for a prolonged period at a temperature of 400° F., and other experiments have shown a considerable loss of strength when tested at still lower temperatures. Much depends on the condition of the metal to begin with. A hard copper loses proportionately more than soft annealed copper, and the result is, perhaps, also dependent on the rate at which the load on the specimen is applied by the

[1] Refer also to Sir W. C. Roberts-Austen's papers on the Measurement of High Temperatures, in Min. Proc. Inst., C. E., Vols. cx., etc. ; also Journal Iron and Steel Inst. and Trans. Inst. Mech. Eng. ; also to Min. Proc. Inst., C. E. Vols. lxxxvi., 462, and xci., 544.

machine. Some experiments of M. Le Chatelier show this time effect well. They were made with some specimens of copper wire :—

TABLE LXII.

Material.	Strength at 60° Fahr.	Strength at 482° Fahr. when the Test lasted.		
		Ten seconds.	Ten minutes.	Thirty minutes.
	Tons per square inch.	Tons per square inch.	Tons per square inch.	Tons per square inch.
Hard Copper	31·75	21·6	15·7	14·43
Soft Copper	15·9	11·9	11·3	10·4

These figures show the great influence of time, and possibly the somewhat discordant results obtained by different observers may here find an explanation."

"M. Le Chatelier maintains that good copper, thoroughly annealed, has a strength of not more than 10 tons per sq. in., when tested at a temperature of 400° F. Even this low figure cannot be relied on in the case of steam pipes with brazed joints, as the quality of the metal is often seriously injured in the neighbourhood of the joint." Small quantities of impurities, such as Arsenic or Bismuth, often found in copper, also act in lowering the strength and ductility of the metal, just as sulphur and other impurities do with steel. "Coming to alloys, many of these are far from reliable at high temperatures. Different samples of gun-metal show widely varying results. Some specimens lose rapidly in strength as the temperature is raised, whilst others, in particular those containing phosphorus, show much more favourable results.

"Aluminium bronze in the rolled state also preserves its strength well, but with castings the results are less favourable."

Experiments on a variety of alloys were made at the instance of the Phosphor-Bronze Company by Mr. Stanger. The following[1]

[1] *Engineering*, Aug. 9th, 1895, p.187.

are the results obtained with a special alloy, which was called by the Company "malleable bronze."

TABLE LXIII.

Material.	Temperature Deg. F.	Breaking Stress. tons per sq. in.	Elastic Limit. tons per sq. in.	Extension per cent. on 6 ins.	Reduction of area per cent.
Rolled malleable bronze	cold	31·51	29·19	8·2	61·0
Malleable bronze	"	28·82	27·54	9·0	71·8
" "	400	27·49	23·42	8·3	68·9
" "	500	26·11	24·70	9·0	67·0
" "	600	25·51	21·39	10·8	62·3

A large number of experiments with other metals and alloys are summarised in Table LXIV. on page 316.

"The figures given for gun-metal show a critical point in the temperature strength curve at about 350° and 400° F., since there is a sudden decrease there in the strength and elongation. An increase in the proportion of zinc and a decrease in that of the tin appear to raise the critical point somewhat, as shown in the figures referring to the brassy gun-metal in next columns. In fact, generally speaking, the zinc-copper alloys are much less sensitive to temperature changes than the tin-copper ones, as the results for yellow metal and naval brass show. The addition of 1 per cent. of aluminium to brass is stated by M. Le Chatelier to improve its behaviour in this respect; common castings with this addition, totally untreated in any way, show, he states, a strength of 12·5 tons per square inch when tested at a temperature of 480° F. He therefore recommends the use of this alloy for boiler fittings in place of the gun-metal usually adopted."

TABLE LXIV.

TENACITY OF METALS AND ALLOYS AT VARIOUS TEMPERATURES.

TENSILE STRENGTH AND ELASTIC LIMITS IN TONS PER SQUARE INCH. ELONGATION IN PER CENT.

TEMPERATURE.	BAR IRON.		BOILER PLATE IRON.		MILD STEEL.		YELLOW METAL			NAVAL BRASS.			ROLLED BULL'S METAL.						COG-WHEEL BRAND PHOSPHOR-BRONZE.					GUN-METAL. Copper 87.78, Tin 9.72, Zinc 2.50		BRASSY GUN METAL. Copper 83, Tin 2, Zinc 15	
							ROLLED.			ROLLED			SOFT QUALITY.			HARD QUALITY.			CAST.		ROLLED.						
	Tensile.	Elongation.	Tensile.	Elongation.	Tensile.	Elongation.	Tensile.	Elastic Limit.	Elongation in 10 In.	Tensile.	Elastic Limit.	Elongation in 10 In.	Tensile.	Elastic Limit.	Elongation in 6 In.	Tensile.	Elastic Limit.	Elongation in 10 In.	Tensile.	Elongation.	Tensile.	Elastic Limit.	Elongation in 10 In.	Tensile.	Elongation.	Tensile.	Elongation.
Atmos. temp.	21.10	15.60	23.90	24.00	28.5	22	25.04	16.10	27.1	27.15	18.95	19.1	32.69	28.72	18.3	42.16	34.78	..	17.4	17.5	30.61	27.76	6.3	15.30	12.50	13.86	26.00
Degs. 100	21.40	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	2 in. 12.5	17.55	17.0	..	..	2 in. 27.7	14.43	10.00	13.71	28.00
150	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	17.43	18.0	..	..	..	15.00	11.00	12.86	25.50
200	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	17.28	18.0	..	..	..	13.86	10.00	13.16	23.25
250	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	16.57	15.0	..	..	..	14.43	10.00	12.56	26.00
300	22.25	..	..	..	..	..	..	..	..	..	..	..	27.10	22.66	18.0	..	..	..	16.42	12.0	..	..	..	14.28	10.00	12.41	23.00
350	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	13.15	7.0	..	..	..	12.86	8.26	12.41	25.00
400	..	..	..		28.4	18.75	21.47	14.21	28.7	23.53	16.74	16.2	25.35	21.07	19.8	39.03	34.14	5.8	12.11	5.0	30.15	28.82	8.2	7.00	0.75	12.41	25.00
450	..	..	27.00	8.00	430 deg. .. 83	..	..	..	2 in. 39.1	..	..	2 in. 21.0	..	..	..	..	..	2 in. 17.0	10.86	4.0	..	..	2 in. 16.5	7.57	nil	4.34	1.20
500	24.40	12.50	27.40	12.00		17.2	20.05	14.24	27.0	23.56	18.95	13.8	.	..	.	33.27	28.81	7.8	12.00	5.0	27.13	21.20	9.0	7.14	nil	4.31	nil
550 to 600	19.30	18.75	..	..	550 deg. 18.6; 580 deg.	25	..	..	2 in. 40.0	..	.	2 in. 18.8	.	.	..	..	..	2 in. 25.0	..	..	..	..	2 in. 23.4				

The following diagram (Fig. 141) represents graphically the results of a number of different experiments on iron and steel, and gives them in a convenient form for comparison.

It was taken by Professor R. H. Thurston[1] from German sources, and he gives the following explanatory notes :—

"Curves Nos. 1 and 2 represent Kollmann's experiments on iron and 3 on Bessemer steel. No. 1 is ordinary and 2 is steely puddled iron.

"Curve No. 4 represents the work of the Franklin Institute on wrought iron.

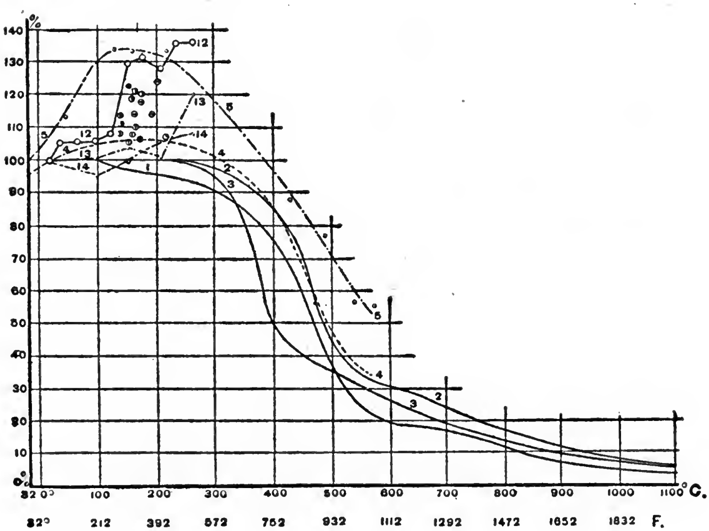


FIG. 141.

"Curve No. 5 gives Fairbairn's results, working on English wrought iron.

"Nos. 6 to 11 are Styffe's, and represent the experiments made by him on Swedish iron. The numbers do not appear, as these results do not fall into curves ; these results are indicated by circles, each group being identified by the peculiar filling of the circles, as one set by a line crossing the centre, another by one across, a third by a full circle, etc.

[1] "Manual of Steam Boilers," etc., p. 83.

"The broken lines 12 and 13 are British Admiralty experiments on blacksmith's irons, and No. 14 on Siemens' steel. The first five series only are of value as indicating any law; and they exhibit the general tendency to a decrease of tenacity with increase of temperature.

"Fairbairn's experiments, No. 5, best exhibit the maximum, first noted by the Committee of the Franklin Institute, at a temperature between that of boiling water and the red heat.

"It will be observed that the measure of tenacity, at the left, is obtained by making the maximum of Kollmann unity. It will also be noted that Kollmann does not find a maximum as in curves 4 and 5, but, on the contrary, a more rapid reduction in strength at that temperature than beyond. It would seem, therefore, that that peculiar phenomenon must be due to some accidental quality of the iron. The author has attributed it to the existence in the iron, before test, of internal stresses which were relieved by flow as the metal was heated, disappearing at a temperature of 300° or 400° F. (149° to 294° C.)."

M. Cornut's Considerations.—With reference, however, to all the results which have been obtained with iron and steel when heated, it has been pointed out by M. Cornut,[1] engineer-in-chief to the North of France Association of Proprietors of Steam Boilers, that the strains have been referred to the original cross-section of the specimen, as measured before being tested, and not to the cross-section at the moment of fracture or at the temperature to which the specimen had been raised. As it appears that the loss of ductility experienced by iron and steel when heated between certain temperatures causes the section of fracture of a bar to be larger at these temperatures than at the normal temperature, it seems to be necessary to ascertain by measurement what are the dimensions of the section at fracture, and to make some corrections for increase of size and increase of brittleness with increased temperature.

One of the most recent writings on the subject is entitled "La Temperature et les Propriétés Resistantes des Metaux," in the Bulletin de la Société d'encouragement pour l'Industrie Nationale, for August, 1899, Tome iv., Series 5, No. 8, pp. 1157–1200.

[1] Translated by B. F. Isherwood in Journal of the Franklin Inst., Vol. cxix., pp. 257–266.

Reference should also be made to an exhaustive series of experiments on the strength and ductility of bronze in relation to temperature which is described by C. Bach in the "Zeitschrift des Vereins Deutscher Ingenieure." A translation into English appeared in the *Engineer* of 5th April, 1901, p. 340.

For these tests 25 cast bronze bars were supplied by the Imperial Dockyard at Kiel, the tests being carried out as follows :—

A. Four bars at the ordinary temperature of 64° to 77° Fahr.
B. Four " " 212° Fahr.
C. Four " " 392° "
D. Five " " 572° "
E. Four " " 752° "
F. Four " " 932° "

The bronze was understood to have the composition 91 parts of copper, 4 parts of zinc, and 5 parts of tin, but analyses made of (*a*) turnings from the first four bars, the result being an average ; and of (*b*) turnings, afterwards taken from bars 2 and 4, yielded the following results :—

		Turnings from all 4 bars (*a*)	Turnings from (*b*) Bar 2.	Bar 4.
Copper	per. cent.	91·35	91·49	91·43
Tin	" "	5·45	5·45	5·50
Zinc	" "	2·87	2·75	2·78
Lead...	" "	0·280	0·273	0·280
Iron	" "	0·025	0·028	0·030
Phosphorus... ...	" "	trace	trace	trace
Arsenic	" "	"	"	"
Antimony	" "	"	"	"
Sulphur, etc. ...	" "	"	"	"

Summary of Tests.—The bronze tested which at ordinary temperatures had a breaking stress Kz of 15·30 tons per sq. inch, an extension ϕ of 36·27 per cent., and a reduction in sectional area ψ of 52·1 per cent., had the following values at the temperatures noted :—

Temperatures Fahr.	212°	392°	572°	752°	932°
Kz	15·47	14·541	8.705	3·954	2·804
ϕ	35·4	34·7	11·5	0	0
ψ	47·4	48·2	16·2	0	0

If the values at ordinary temperatures be taken in each case as 1, then the following proportional figures are obtained :—

Breaking stress at

	68° F.	212° F.	392° F.	572° F.	752° F.	932° F.
	15·30 tons	15·457 tons	14·541	8·705	3·954	2·804
=	1	1·01	0·94	0·57	0·26	0·18

so that at 392° F. the breaking stress is reduced by 6 per cent., at 572° by 43 per cent., at 752° by 74 per cent., and at 932 by 82 per cent.

The final extension at 212° is 0·98 (unity being 36·3), at 392° it is 0·96, at 572° it is 0·32 or 68 per cent. reduction, at 752° further extension can no longer be detected.

Reduction of sectional area follows a similar order :—

	at 68° F.	212° F.	392° F.	572° F.	752° F.	932° F.
	52·1	47·4	48·2	16·2	0	0
=	1	0·91	0·93	0·31	0	0

It follows that the bronze tested might be used for valves pipes, etc., with steam at a temperature of 392° F., but not in any case with steam at 572° F. If that limit is exceeded the greatest caution should be observed.

In no case should such bronze be used for pipes, etc., which are to carry highly superheated steam, and even with moderately superheated steam its use is not advisable.

Further experiments are in progress as to the results with bronze of different composition.

Although 572° F. is the temperature estimated for saturated steam of 1,000 lbs. per sq. inch pressure, yet it may be reached by superheated steam of a much less pressure, and therefore the use of such bronze may be attended with considerable risk.

CHAPTER VII.

Corrosion and Incrustation in Boilers.

The preservation of boilers from chemical actions is now fairly well understood to be almost entirely a question of cleanliness. Given boiler surfaces of a good quality of material, kept free from deposits of foreign metallic, earthy, or oily matters, and supplied with fresh water from which the suspended or dissolved gases have been removed and are excluded, and there is no fear of destructive actions proceeding.

For a long time after the introduction of compound marine engines with surface condensers—say, from 1856 onwards[1] for many years—engineers had to face a difficulty which to former practice had been almost a total stranger, and had to combat, whilst they at the same time investigated, the apparently erratic and mysterious ravages of corrosion.

Formerly the use of sea water in marine boilers, like that of calcareous waters on land, resulted in a greater or less thickness of incrustation being formed on the interior boiler surfaces. Unless this was allowed to form to a considerable extent on the parts of plates or tubes exposed to the direct heat of the fire or furnace, however, there was no danger of destructive action due to the presence of such solid deposits. They could be in a large measure held in check by the use of precipitants, with periodical blowing off the mud from the boilers, on land, or by the use of brine chests or regular blowing off a portion of the contents of the boilers, so as to regulate the density of the water in the boiler, in marine practice. No doubt this practice was more or less barbarous, and involved in several ways the loss of heat; but as long as deposits of lime or magnesia coated the inner surfaces of boilers they were safe from corrosive action from within. We can now see that in the days when tallow was allowed to find its way in almost unlimited quantities from the engines to the boilers, such a protection must have been of real

[1] See Trans. Inst. E. and S. in Scot., Vol. xxii., pp. 51-78; Trans. Inst. Naval Arch., Vol. xxx., pp. 108, 109.

service to them. These were not the days when the last thermal unit was demanded from the fuel, and the highest efficiency in both boiler and engine was striven for, and consequently engineers and shipowners did not object to waste a few tons of coal, and to get on with fewer horse-power, or less speed, so long as boilers could be readily worked, and easily protected when out of action. At the same time, it must not be supposed that engineers knew they were wasting fuel, or working more inefficiently than was necessary, but only that, certain arrangements having been arrived at, by means of the ordinary process of selection of the readiest method, there was no pressing reason for seeking improvement by the inevitable path of pain and trouble. According to the law of progress, however, that was bound to come, and the improvement of the steam engine and spread of the science of thermo-dynamics introduced the inevitable.

When the question of boiler corrosion came to be faced, there had been but little real advance made by way of examining the main subject of corrosion of metals. Locomotive engineers had experienced some trouble from corrosion in their boilers, but the principal investigations carried out in connection with the subject had been made either as scientific experiments or in view of the durability of iron structures, such as bridges or ships.

Undoubtedly there were several workers in this field, and some isolated facts concerning the corrosion of iron had been observed. The reports made by Mr. R. Mallet, M.R.I.A., to the British Association (Reports 1838, p. 253; 1840, p. 221-308; and 1843, p. 1-53) give a useful summary of the information available at the time when his experiments were undertaken. It was thus made known that dry air and dry oxygen have no action on iron below ignition temperature, that pure water deprived of air also has no action below 212° F., and that at common temperatures air and water combined act energetically in producing rusting or oxidation. Professor Bonsdorf, of Helsingfors, had added the information that air perfectly dry, or air saturated with water vapour, if free from carbonic acid, has no action on iron; but where both are present, and also, as above, in contact with both air and water, there is active oxidation. The action of sea water at different depths and different temperatures was also to some extent studied; but these researches

remained but little known until 1872, when Mr. Mallet read a paper on "The Corrosion and Fouling of Iron Ships" to the Institute of Naval Architects (vol. xiii., pp. 90-162). Even then, however, the application of these researches to steam boilers did not at once appear, and did not, consequently, suggest itself to engineers.

Such papers, moreover, as those "On Surface Condensation in Marine Engines," by Mr. Edward Humphrys, of Deptford, and "On the Effects of Surface Condensers on Steam Boilers," by Mr. James Jack, of Liverpool, in Proceedings of the Institution of Mechanical Engineers, 1862, page 99; and 1863, page 150, whilst publishing, or eliciting by means of discussion, the main facts as to the corrosion which became troublesome in boilers contemporaneously with the use of surface condensers, served to make it apparent that engineers were ignorant both of its cause and of a remedy for it. In fact, the conclusion emerging from both these papers and discussions is that, whilst some corrosion was believed to be due to fatty acids resulting from decomposition of grease, and some to the presence of particles of brass and copper in the boiler, yet the real cause of the corrosion was believed to be the "distilled water itself," so that, as they expressed it, "by constantly boiling the same water over and over again it was robbed of some of its original properties, or became otherwise altered in quality thereby, so as to produce the serious effects that were experienced." To Faraday[1] are due the suggestions that the chloride of magnesium in sea water is capable of the most powerful action on the plates of boilers, and that voltaic action may arise in a boiler through the contact of copper and iron. Others, such as Mr. F. A. Paget, following R. Mallet, F.R.S., added to that the idea that voltaic action might be due to dissimilarity in composition or texture between different plates, or even portions of the same plates, in a boiler; and one observer announced that the steam escaping from the safety valve of a boiler using sea-water showed a distinctly acid reaction, some of the corrosion being ascribed to this as a cause.

The first direct light which was thrown upon the subject of corrosion in marine boilers was obtained from some careful

[1] Fifth Report of the Committee of the House of Commons concerning the Holyhead Roads, p. 194.

experiments carried out by the late Professor Crace Calvert, of Manchester, whose researches, though published about 1866, were for a long time considered of interest only to chemists to whom they were known. Calvert showed incontestably the effect of oxygen and carbonic acid (carbon-dioxide) on metals in presence of moisture, and demonstrated that distilled water free from air or gases (and even that dry oxygen or dry carbonic acid) has no corrosive action on pure iron or steel. Mr. W. Kent, a distinguished member of the Stevens Institute of Technology, at an early date recognised the practical value of these investigations, and by means of them was able to explain satisfactorily the corrosion of iron railway bridges in the United States of America.[1] Their application to the case of boilers was first pointed out by the author of this work in 1876,[2] who quoted (see Appendix III., pp. 616, 617) in support of them the results of later researches by Professor A. Wagner, which also established the fact that the presence of chlorides of magnesium sodium, calcium, and other chlorides mentioned by him, caused the rusting of iron, their action being greatly increased by the concurrent presence of air and carbonic acid in solution in the water, except in the case of magnesium chloride, which attacked iron in the absence of air.

In the same paper (See Appendix III., pp. 618, 619) the results of a careful examination of the effects of grease in condensed water on boilers were given, so that the range of that action should be understood; and some notice will be found in it of the subjects of the decomposition of the chlorides in sea-water, of the presence and liberation of carbonic acid therein under the action of heat and pressure, and of the possibility of galvanic action being to a limited extent due to particles of copper and brass from the engines carried into the boilers.

About twelve months after the appearance of the author's paper "On Boiler Incrustation and Corrosion," or in August, 1877, the third Report of the Admiralty "Committee appointed to inquire into the causes of the deterioration of boilers," etc.,

[1] See the *Engineer* of Aug. 13th, 1875.

[2] "On Boiler Incrustation and Corrosion," by F. J. Rowan, read before Section G, British Association, Glasgow, 1876, and recommended for publication by Section G, As this paper is out of print, it is reproduced in Appendix III.

was issued (the previous two reports having been of a preliminary character), and in it the results of their protracted inquiry were given, as well as the conclusions at which they had arrived as to the causes of corrosive action. This third Report emphasised the same facts which had already been published by the author, but advanced no new views as to the sources of corrosion. Since the latter date (August, 1877) papers on this subject have been written by Mr. D. Phillips,[1] formerly an engineer on the Admiralty Committee, by Mr. J. Farquharson,[2] who conducted experiments for the second Committee (which was a departmental one) appointed to carry on the investigation after the first Committee was dissolved; by Mr. W. J. Norris,[3] Mr. W. Parker,[4] Mr. J. B. Dodds,[5] Prof. V. B. Lewes,[6] Mr. J. H. Hallett,[7] Mr. C. C. Lindsay, Mr. Sinclair Couper,[8] and others, and reports have been issued by the second or departmental Committee of the Admiralty. An interesting paper on "Feed-water, its Effect on Steam Boilers and its Treatment," read by Mr. E. G. Constantine, M.I.M.E., to the Manchester Association of Engineers, in April, 1890, may be consulted; the papers by Mr. Thos. Andrews, F.R.S.E., on "Galvanic Action, etc.," in Trans. Roy. Soc. Edin., and in Min. Proc. Inst. C.E., should be carefully considered; and also an important paper by Mr. Thos. Turner, A.R.S.M., F.I.C., Lecturer on Metallurgy at Mason's College, Birmingham, on "The Corrosion of Iron and Steel," read to the South Staffordshire Inst. of Iron and Steel Works Managers in February, 1894.

Relative Corrosion of Iron and Steel.—The investigations and papers by Mr. Phillips, Mr. Farquharson, and Mr. Parker, were occupied principally with the question of the comparative rates of wasting or corrosion in iron and mild steel, and it appeared that, in general, mild steel, perhaps on account of its purity, is

[1] Min. Proc. Inst. C. E., Vols. lxv., pp. 73-97 and 98-138, and Vol. lxxxv. p. 295.

[2] Trans. Inst. N. A., Vol. xxiii. (1882), pp. 143-150.

[3] Trans. Inst. N. A., Vol. xxiii., pp. 151-162.

[4] Jour. Iron and Steel Inst., 1879, p. 53 and 1881, p. 49.

[5] Trans. N.E. Coast Inst. Eng. and S., Vol. v., p. 195.

[6] Trans. Inst. N. A., Vol. xxviii., p. 247, Vol. xxx., pp. 330-362, and Vol. xxxii., p. 67.

[7] Proc. Inst. Mech. Eng., 1884, p. 331.

[8] Trans. Inst. E. and S. in Scotland, Vol. xl., pp. 41-106, Vol. xxiv., pp. 77-118.

more liable to rapid oxidation than wrought iron, as wrought iron in this matter precedes cast iron. When, however, both wrought iron and steel plates were used in the same structure, or where steel plates were fastened with wrought-iron rivets, the results were conflicting ; in some cases the steel, and in others the iron, showed the greater amount of corrosion.

As the main question here is not steel *versus* iron, but is the action of corrosion and how to prevent it, we must practically pass over these papers and many experiments made by or at the instance of both Committees on boilers. The main facts as to the relative corrosion of iron and steel have been well summarised by Mr. Turner in the paper referred to. The following is an extract from it :—

"The differences of opinion on this subject have arisen, the author believes, on account of conclusions being drawn from limited observation, or special circumstances ; while much confusion has arisen from failing to recognise that the conditions in fresh water, salt water, the interior of a boiler, or in diluted acids, are all different, and that a specimen which may very successfully resist corrosion in one of these cases may readily oxidize in another. On account of the greater uniformity in the physical properties of steel, and the laminated character of iron, it was anticipated in the early days of the use of mild steel that it would resist corrosion much better than wrought iron. Thus Sir L. Bell[1] expressed the opinion that the cinder in wrought-iron rails would set up galvanic currents, and thus lead to more rapid corrosion. Experience has however shown that on lines where there is very little traffic, and the chief agent of destruction is corrosion, wrought-iron rails wear better than steel.

"The result of the experiments of the Admiralty Committees which were appointed to consider the causes of the deterioration of boilers, and which issued Reports in 1877 and 1880, led to the conclusion that in all cases wrought iron resisted corrosion better than steel. Where the conditions were not severe the differences observed were not great ; but where the plates were daily dipped in water, and exposed during the rest of the time to the action of the atmosphere, the superiority of iron was very

[1] Jour. Iron and Steel Inst., Vol. i., 1878, p. 97.

marked; while common iron was less affected by corrosion than best Yorkshire iron, which is in accordance with the statement of Gmelin that phosphorus diminishes corrosion in iron. The following percentages in favour of iron were obtained in these experiments :—

Common iron resisted corrosion better than Yorkshire iron	9·6 per cent.
Yorkshire iron resisted corrosion better than mild steel	16·0 ,,

"In another series of experiments, conducted by Mr. D. Phillips, in Cardigan Bay, and lasting for seven years, it was found that the average corrosion of mild steel during the whole period was 126 per cent. more than wrought iron.[1] Independent experiments conducted by Mr. T. Andrews[2] also showed that wrought iron corroded less rapidly than mild steel, when the cleaned metallic surfaces were exposed to the action of sea-water. The conclusions of the Admiralty Committee and of Mr. Phillips aroused much adverse criticism, and it was shown that though steel is more affected by ordinary atmospheric corrosion, it is not usually more affected when in the form of a steel boiler. This was stated by Mr. W. Parker,[3] who based his conclusions on the result of over 1,100 actual examinations of boilers; and his observations were confirmed by experienced makers and users of boilers, who took part in the discussion of his paper."

Sir W. Siemens also stated that experiments at Landore had shown similar results, and Sir H. Bessemer[4] bore testimony to the same effect, while "Mr. W. John,[5] as the result of considerable experience in the construction of ships, stated that the protection of mild steel ships from corrosion was purely a question of care and maintenance, and the correctness of this view has been fully proved in the interval that has since elapsed.

"It is generally believed that the presence of manganese in steel increases the readiness with which it rusts or corrodes.

[1] Min. Proc. Inst. C. E., Vol. lxv., p. 73 ; Proc. Inst. Mar. Eng., May, 1890.
[2] Min. Proc. Inst. C. E., Vol. lxxvii., p. 323, Vol. lxxxii., p. 281.
[3] Jour. Iron and Steel Inst., Vol. i., 1881, p. 39.
[4] Min. Proc. Inst. C. E., Vol. lxv., p. 101.
[5] Jour. Iron and Steel Inst., Vol. i., 1884, p. 151.

"This view was held by Sir W. Siemens,[1] who stated that as manganese in mild steel increased, so the tendency to corrode became greater; while Mr. G. J. Snelus[2] has ascribed the 'pitting' in steel to the irregular distribution of manganese in the metal."

The experiments of Faraday led him to the conclusion that most of the alloys of steel with other metals corrode less readily in moist air than unalloyed steel; but, according to Mallet,[3] the alloys of potassium, sodium, barium, aluminium, manganese, silver, platinum, antimony and arsenic with iron, corrode more rapidly than pure iron; while the presence of nickel, cobalt, tin, copper, mercury and chromium affords protection, the effect being in each case in the order given.

Later French writings confirm this as regards the presence of nickel.

Evidence of Bias in Papers.—Regarding the later writings on boiler corrosion, a curious phenomenon is often seen in the publications or papers dealing with this subject. An author desires to show that corrosion in boilers always proceeds from one particular cause, which he is satisfied is the true one. He thereupon gives details or descriptions of other causes which have been suggested by others, and is careful to call them "theories," in an objectionable way, *i.e.*, with the view of discrediting them out of hand or of prejudicing opinion about them. He then selects examples of corrosion which do not fit, and doubtless, were never supposed to fit, any of these so-called "theoretical" causes, but which do fit in with the one which he has selected for approval, and thus he conclusively proves his point and triumphantly dismisses the defamed "theories." A little consideration would, however, show that it is never supposed by any who have studied the subject that there is one universal cause for all instances of corrosion, or that any special cause dominates every case unless an exceptional one. There are several causes or agencies usually at work, and not all are to be found operative in any one case, nor are the same ones operative in each case. Usually certain causes are more prominently found in one case, and different ones in another; the conditions under which the individual boiler is worked having

[1] Jour. Iron and Steel Inst, Vol. i., 1878, p. 44.
[2] Jour. Iron and Steel Inst., Vol. i., 1881, p. 66.
[3] B. A. Reports, 1838, p. 266.

naturally a great influence on the special kind of action to which it becomes subject.

Another thing becomes evident on a survey of the literature of corrosion, and that is that the answer to the objections or difficulties of one author or investigator is usually to be found at hand in the work of another, not seldom having been published before the appearance of the objection.

Galvanic Action.—It is remarkable that in the records of all the earlier researches into corrosive action, the greatest stress was laid upon voltaic action, or what was termed the action of galvanic currents, as being the prime *cause* of corrosion. This was usually expressed in such a way as to convey the idea that the mere presence of dissimilar metals, or qualities of metal, in contact, is enough to start corrosive action, and that, as even a modern chemist has expressed it, "there must be great chemical action due to the formation of a galvanic current." While, however, it is true that the passage of an electric current through a liquid between metals or bodies of opposite relations, considered electrically, causes chemical action to take place by which one element becomes corroded or eaten away; yet the analogy of a galvanic cell shows that it is the chemical action which causes the appearance of an electric current, so that to say "the chemical action due to the *formation* of a galvanic current," seems to reverse the proper order. No one can say that the statement is wrong, nevertheless, because, for all that we know, the electric may be the initiatory and directive form of the energy which first becomes sensible to us as chemical action. Where there is such chemical action proceeding as the union of a metal (such as iron) with oxygen, resulting in the formation of oxide, there is certain to be the evidence of more or less heat and electricity. When under such circumstances electrically dissimilar metals or substances are present in contact, the effect of that arrangement is to determine the direction of flow of the electrical energy, which becomes apparent as current, so that the electro-positive element becomes the one which suffers most from the chemical action. It has, however, been proved that in some cases—and the oxidation or rusting of iron is one of them—the accumulation of oxygen at the positive pole has the effect of in time polarising the galvanic couple and the action is hindered if not reversed. In some instances of corrosion a reversal of the

direction of the electrical current has been noticed. It was pointed out by Mr. D. Phillips[1] that while in some cases much local action had been observed when iron rivets had been used in steel boilers, there were numerous cases of such construction where no injurious effects had been noticed. Some experiments communicated to the Institution of Marine Engineers by Mr. J. Farquharson[2] showed that while some steel plates which were tested alone "lost about 12 ounces by corrosion and iron plates when similarly tested lost about 11 ounces, if the two dissimilar plates were in electric contact, the steel lost only about 4 ounces, while the iron lost 21 ounces," showing that in this case, at all events, the iron, from whatever cause, acted as electro-positive to the steel. Mr. W. Denny[3] also recorded the case of a steel ship in which the corrosion shown was "not in the steel, but in the iron stern-frame and rudder forgings and in some small iron plates on the rudder, the large steel plates of the rudder and the whole shell plating of the ship, which was of steel, being perfectly free from corrosion." On the other hand Mr. B. Martell[4] instanced the case of a steel ship which he had examined in the North of England (when hauled up on a slip-way after less than a year's employment at sea) as having shown rapid deterioration of the steel plates where they had been exposed alternately to sea-water and to air. "The vessel was riveted with iron rivets, and he found that between the light-water mark and the load-water mark, which was alternately wet with sea-water and then dry and exposed to the air, a rapid deterioration had taken place as compared with the other parts of the vessel, and with iron vessels; in fact, the steel round the rivets had wasted to a considerable extent, so that the rivet points were protruding some distance beyond the steel. He thought it might probably be due to galvanic action." It is evident that, as Mr. Turner has suggested, the explanation of the apparently contradictory results noticed by previous observers is probably to be found in the observations by Mr. T. Andrews[5]

[1] Proc. Inst. Marine Eng., May, 1890.

[2] Proc. Inst. Marine Eng., March, 1882.

[3] Jour. Iron and Steel Inst., Vol. i., 1881, p. 63.

[4] Min. Proc. Inst. C. E., Vol. lxv., p. 103.

[5] Min. Proc. Inst. C. E., Vol. lxxvii., pp. 323-334. See also Trans. Roy. Soc. Edin., Vol. xxxii., pp. 204-218.

in the course of some experiments on the galvanic action between different varieties of iron and steel during exposure to sea-water. "In these experiments metal of known chemical composition was employed in the form of round rods which were carefully turned and polished before use. The rods were immersed in sea-water in a standard cell, together with a standard rod of wrought iron, and frequent observations of the electro-motive force of the couple were made with a delicate galvanometer. Though it was observed that the standard wrought-iron was electro-negative to all the samples tested, it was also noticed during a lengthy course of experiments, that a complete interchange of electro-chemical position occurred in the case of every metal at various times during the observations. These interchanges of position sometimes took place even after considerable intervals, and it is doubtful whether a permanent position of rest finally ensues between the two metals, though eventually the galvanic action becomes very small." These results were afterwards corroborated by some gravimetrical experiments carried out by Mr. Andrews and communicated to the Inst. C. E.[1] There is little doubt that they supply the explanation sought for.

Mr. Andrews also communicated the results of a series of experiments to the Royal Society of Edinburgh[2] which showed that " wrought-iron and steels are not static in their electro-chemical positions, and when immersed in sea-water, or other solutions, in connection with each other, cannot exactly be regarded as constant elements. The relative electro-chemical position is also varied according to the nature of the solutions employed."

Full details of the chemical constitution and physical properties of the various specimens of steel, wrought and cast-iron used in the tests, are given in a series of Tables in Mr. Andrews' paper, which must be consulted for these details. Tables of the galvanic tests, and curves graphically representing the results, are also given, and these show that although the galvanic action is usually vigorous on starting with bright and clean surfaces, yet the accumulation of oxide soon diminishes its activity and frequently reversals of polarity become evident.

[1] Min. Proc. Inst. C. E., Vol. lxxxii., p. 281. See also Vol. cxviii., p. 356.

[2] Transactions, Vol. xxxii., pp.204-218.

In general, in sea-water, all the steels as well as the wrought iron and cast iron appeared on first being immersed to be negative to zinc rods, when these formed the other member of the couples.

Soft Siemens-Martin steel, cast iron and Tungsten steel appeared to be positive to the wrought-iron standard bar employed by Mr. Andrews, whilst both hard and soft Firth's steel, Bessemer steel, puddled steel and puddled steel chilled were electro-negative to the wrought iron.

All these metals without distinction appeared on immersion in sea-water to be positive to bars of iron coated with the oxide from the rolling mills.

In acid colliery water all the metals were negative to zinc; all were negative to the wrought-iron bars, except Tungsten steel, which was first positive and afterwards negative. All were positive to bars coated with iron scale.

In sea-water also all the metals in the form of plates with bright surfaces were positive to bright copper plates.

A series of plates were prepared bent in the form of an inverted **U** (thus **∩**), having one limb polished bright, and the other coated with mill scale, and these were immersed in sea-water in porous cells and coupled together in series electrically. The bright side was invariably positive to that coated with oxide, and the action was at first energetic between them, but in the course of about four days the current diminished and died away to almost nothing.

"It may therefore be concluded," writes Mr. Turner, "that though with dissimilar metals, such as cast iron and wrought iron, the galvanic action may be considerable, in the case of materials which are more alike, such as wrought iron and mild steel, it is exceptional for the corrosion from galvanic action to be very great, although its occurrence should never be overlooked; and when this action does occur, though it usually leads to the corrosion of the steel, yet it not infrequently has a contrary influence. The danger of greatly increased corrosion with dissimilar metals is much diminished by their tendency to polarize each other's action, and thus lead to an interchange of electro-chemical position. Galvanic action between wrought iron and steels also appears to be materially reduced in course of time, otherwise the liability to destructive

corrosion, though never inconsiderable, would be more formidable."

Influence of Stress on Corrosion.—We are indebted to Mr. Andrews[1] for the further research which has demonstrated the effect of stress on corrosive action. It was known that stress, whether tensile, flexional, torsional, or of any other kind, considerably alters the physical properties of iron and steel; increases the rigidity of both iron and steel, and renders the metal harder, also greatly reducing its properties of elongation or ductility. "A higher tonnage is required to break a 'strained' than an 'unstrained' portion of the same metal. A tensile stress applied to a wrought-iron shaft, producing an elongation of only 2 per cent. increased the tensile resistance of the metal 2·66 per cent." "It is manifest," Mr. Andrews remarked, "that the stresses, applied to the metals examined for corrosion, altered their structure, rendered them harder in nature, and hence less liable in the strained condition to be acted upon by sea-water, or other waters, than in their ordinary or softer condition. The experiments, however, indicated that an increased total corrosion, in excess of the normal corrosibility of the metal, occurs in a metallic bridge, vessel, boiler, or other structure from the action of the local galvanic currents which were shown to be induced between 'strained' and 'unstrained' portions of even the same piece of iron or steel forging, bar, or plate. Hence a strain occurring in a metallic structure tends, owing to the local galvanic action thus set up, to increase any corrosive forces which may be deteriorating the metal of which it is composed." The explanation of the corrosion of ship's plates between punched rivet holes may be found in this, and reflectively it supplies an argument against punching. Such researches throw needed light upon the causes which determine the course and the rapidity of corrosive action, but it must be remembered that were all other elements of chemical action absent, the mere presence of dissimilar electro-chemical or physical qualities in metals in contact could not of itself create corrosive action. That is to say, that if dissimilar metals or qualities of metal were in metallic contact, and immersed in a liquid which has no

[1] Min. Proc. Inst. C. E., Vol. cxviii., p. 356. See also Proc. Royal Soc., Vols. xlii., 459; xliv., 152; xlvi., 176; lii., 114; Proc. Fed. Inst. Mining Engineers, Vol. i., 191; Min. Proc. Inst. C.E., Vols. lxxxvii., 340; xciv., 180; cv., 161.

chemical action, or contains no gases which have chemical action, on the metal, there would not be any evidence of galvanic current. But, conversely, where chemical action is present, combined with electro-chemical dissimilarity, there must be galvanic action, in spite of such reasoning as that of Mr. W. J. Norris[1] to the contrary. The distinguishing characteristics of chemical action that is entirely local and of that which is, or may become voltaic, are, of course, not entered into here.

Influence of Mill Scale or Oxide.—The presence of mill scale, or that quality of black oxide which is produced in rolling mill or forge furnaces, on the surface of iron or steel, has been found to be an active cause of the production of galvanic currrents in a sense adverse to the metal plates to which the scale adheres.

Electrical Activity of Oxides.—Mr. Andrews' experiments demonstrate the reason, and the fact that damage is caused when such scale is present is abundantly testified to by Mr. W. Parker,[2] Sir N. Barnaby,[3] Sir W. H. White,[4] Mr. J. Farquharson,[5] and Professor V. B. Lewes.[6] The latter made some interesting tests, comparing the electrical activity of the oxides with that of the metal. "Some steel plates, 4 inches by 1 inch, were cut from the same sheet and were faced on one side. On the polished surface of one a piece of thin blotting-paper was laid, so as to entirely cover it, and project half an inch beyond its edges. This was wetted with sea-water, and the other plate, with its polished face downwards, was placed on the wet paper, so that the two polished steel faces were separated by the blotting-paper soaked with sea-water. Wires were then placed in contact with the dry backs of the plates, and fixed in position by a dry wooden clamp. On connecting this couple with a Thomson's marine reflecting galvanometer, a deflection of 20° on the scale was obtained. The upper plate was then raised, and smeared over with a thin paste of magnetic oxide mixed with sea-water. It was then replaced in position, giving a deflection of 112° on

[1] See Trans. Inst. N. A., Vol. xxiii. (1882), pp. 151–161 ; also *Engineering*, 28th July, 1882, page 96.

[2] Jour. Iron and Steel Inst., Vol. i., 1881, pp. 48–53.

[3] Jour. Iron and Steel Inst., Vol. i., 1879, p. 53.

[4] Jour. Iron and Steel Inst., Vol. i., 1881, p. 68.

[5] Min. Proc. Inst., C. E., Vol. lxv., p. 105.

[6] Trans. Inst. N. A., Vol. xxviii., 1887, p. 247 ; Jour. Iron and Steel Inst., Vol. i., 1887, p. 461.

the scale. The plates were then carefully cleaned and dried; fresh blotting-paper, moistened with sea-water, was placed in position, and the upper plate was smeared with hydrated ferric oxide and sea-water and placed upon it. This gave a deflection of 65°; whilst hydrated ferrous oxide only gave a deflection of 25°, or very little more than the plates by themselves; portions of a rust cone treated in the same way gave a deflection of 110°. In each case the reading was taken immediately the needle came to rest, and in all cases the current rapidly diminished, but generally recovered again on standing in circuit. A small cell made of crushed rust-cones from H.M.S. 'Inflexible,' after standing on short circuit for a week, gave a constant deflection of 108°. These deflections were all much increased on using sea-water through which carbonic acid and air had been passed." This latter only showed that the water was thus made a more active corroding agent, because as the chemical action increases in intensity so the display of electrical energy is more pronounced. From these data Professor Lewes concluded that it is easy to explain the formation of rust cones, and the consequent or concurrent pitting of the plates of ships. "On the metal of the ship there is a small particle of moist rust left when the ship was last scraped, or else formed by a particle of some foreign metal, or the perishing of the protective. The moist rust forms a galvanic couple with the iron, and slowly decomposes the moisture; the oxygen oxidising the iron. The hydrogen, on the other hand, gently pushes up the protective and anti-fouling coats, forming a small blister. The sea-water leaks in, an active galvanic current is produced, and the blister slowly fills with the rust resulting from that action. The continuation of the action gives the larger rust cones. This process being independent of the oxygen dissolved in the sea-water, and the amount of water present being small, the corrosion gives rise to the ferrous as well as the ferric oxide."

On this subject Mr. W. John[1] recorded "the case of a steel ship which had been launched just six weeks and then docked, to receive her engines and boilers; and although she had been carefully painted before launching, with a good composition specially chosen by the owners, many of the plates presented a

[1] Jour. Iron and Steel, Inst., Vol i., 1884, pp. 138-181.

most curious appearance of pitting. They were scattered about in some parts without any apparent connection, and in others, the little mole-hills of rust seemed to have an order of their own, either in curves or straight lines. He was so much struck with the case that he examined it very thoroughly, and as the rust dried in the little mounds he carefully scraped a number of these off with a knife, without injuring the paint." It then appeared that although the rust was formed into little hemispheres of about $\frac{1}{4}$in. diameter outside the paint, the hole in the paint was not more than the size of a pin head, and that in each case it was easy to pick out a loose particle of black oxide embedded in a little pit in the plate, so that the active cause of the local action was very apparent. Although these results have been observed in the case of iron or steel ships immersed in sea-water, yet they are no doubt analogous to those often noticed in the case of boiler plates or tubes. And even where the elements of galvanic action may not be present in any marked degree, yet the chemical processes involved in the corrosion or pitting require very few conditions for their being present in activity.

Summary of Chemical Processes Involved.—These conditions have been referred to already, but may be reviewed in the form of the summary due to Professor Crum Brown.[1] "Liquid water, quite free from dissolved gases, does not act on iron at ordinary temperatures. At high temperatures, very rapidly at a red heat, iron is oxidised by water or water vapour, and is converted into the magnetic oxide of iron. This magnetic oxide is found on the surface of the iron as an adherent coating, and only when it is detached can the water gain access to lower layers of the iron.

"Oxygen gas alone does not act at ordinary temperatures on iron. At high temperatures it also converts the iron into the magnetic oxide which forms an adherent coating. The same is the case with carbonic acid gas, acting alone. At ordinary temperature it is without action. At high temperatures the carbonic acid is reduced to carbonic oxide, and the iron is oxidised to magnetic oxide, which forms an adherent coating."

Liquid water with oxygen dissolved in it will not act at ordinary temperatures on iron if lime be in solution, or any

[1] Jour. Iron and Steel Inst., Vol. ii., 1888, pp. 129-131. See also Trans. Inst. N. A., Vol. xiii., pp. 95, 96.

caustic alkali which is capable of combining with carbonic acid, and is itself without action on iron. But "when the lime or caustic alkali has been converted by the carbonic acid of the air into carbonate, then" free carbonic acid can be absorbed from the air, and rusting will begin.

"Water, containing carbonic acid dissolved in it, acts on iron at ordinary temperatures, forming ferrous carbonate, which dissolves in the carbonic acid water, forming, no doubt, ferrous bicarbonate. In this action hydrogen gas is given off. If oxygen is present, dissolved in the water, it will unite with the nascent hydrogen; and if we have sufficient water, iron and carbonic acid, the whole of the dissolved oxygen will thus be consumed. The presence of dissolved oxygen quickens the solution of the iron, the tendency of the oxygen to combine with the nascent hydrogen supplying an additional *motive* to the action. Probably in ordinary rusting no hydrogen actually becomes free, as under ordinary conditions there will always be enough dissolved oxygen to convert all the nascent hydrogen into water.

"When a solution of ferrous bicarbonate is exposed to an atmosphere containing neither free oxygen nor carbonic acid, it loses carbonic acid, and insoluble ferrous carbonate is precipitated. If free oxygen is present in the atmosphere to which it is exposed, the ferrous carbonate is oxidised to ferric hydrate, carbonic acid being given off. This, if the water is not already saturated with carbonic acid, dissolves in the water." In this way the carbonic acid is not used up in the process, but is repeatedly set free, and becomes ready to act on a new surface of the metallic iron. "The continuation of the process of rusting is not, therefore, dependent on new carbonic acid absorbed from the air, but the original carbonic acid, if not removed, can carry on the process indefinitely, as long as liquid water is present, and oxygen is supplied from the air. Once the process is started it goes on more rapidly, because the porous rust not only does not protect the iron, but favours by its hygroscopic character, the condensation of water vapour from the air as liquid water."

It is to be observed here that the gases referred to, viz., oxygen and carbonic acid, are dissolved in the water and are in a very different state from liquid oxygen and liquid carbonic acid,

which can be produced only at an extremely low temperature. It is therefore a mistaken idea[1] which has been expressed that *as dissolved* "they are in the true liquid state, and behave in every way as liquids." On the contrary, they remain in solution at temperatures far above those at which these gases exist as liquids, and are liberated by heat from the water before it becomes vapourized. It is a further mistake to apply the term "nascent" to the oxygen which thus is liberated from solution—it has not changed its condition; it was absorbed as free oxygen and is liberated in the same state. To have nascent oxygen we should require some chemical action or decomposition as the result of which oxygen that was formerly in chemical combination is liberated. The oxygen and carbonic acid held in suspension by water or dissolved in it are liberated by boiling the water, and the same result follows when the water is placed under the receiver of an air-pump, and the atmospheric pressure is removed. Consequently carbonic acid and oxygen dissolved in water are not "put into the nascent state by the heat transmitted through the metal to the water," any more than they are by being set free under the air-pump; and as we have seen from Dr. Crum Brown's summary, their action upon iron or steel is not dependent upon such an explanation.

Absorption of Gases by Liquids.—Of more interest than any such crude theoretical notions are the questions of the rate of absorption of these gases in water, and the conditions of their liberation therefrom.

In general the amount of a gas absorbed by a liquid upon which it exerts no direct chemical action, depends on the specific nature of the gas and that of the liquid, regulating the degree of solubility of gases in different liquids, on the temperature of the liquid and gas, and on the pressure under which absorption takes place.

With few exceptions, the volume of gas absorbed by a liquid decreases with increase of temperature, and increases with a fall of temperature. It has been said[2] that "in the case of many of the less soluble gases, the alteration in the absorbed volume effected by changes of temperature lying within the range of

[1] "Steam Engine Boiler Feeding," by James Weir. International Engineering Congress, Chicago, 1893.

[2] "Watts' Dict. of Chemistry," Vol. ii., p. 791.

easy experimentation is so small that it can only be detected by accurate observation. Indeed, the earlier chemists, especially Dalton, believed that the amount of gas absorbed was entirely independent of the temperature." As regards the influence of pressure, it has been found that within the limits of the strict application of Boyle's law (that the volume of a gas is inversely proportional to the pressure to which it is subjected), the quantity or weight of gas absorbed by liquid varies directly as the pressure, so that under equal circumstances of temperature more gas is absorbed, as the pressure is greater.

In order to compare the solubility of various gases in liquids, the volume of gas (measured at standard temperature, 0° C., and pressure, 76 mm. of mercury), which is absorbed under a pressure of 76 mm. of mercury in one volume of liquid at the temperature of observation, is determined, and this volume is called the *coefficient of absorption* of that gas in that liquid.

Coefficients of Absorption.—These coefficients have been for the most part determined by Bunsen and his pupils, and the following are amongst their results :—

TABLE LXV.

Gas.	Coefficients of Absorption in Water.	
	At 0° C.	At 20° C.
Nitrogen	0·02035	0·01403
Carbonic Acid	1·7967	0·9014
Oxygen	0·04114	0·02838
Atmospheric Air	0·02471	0·01704

The effects of variation of pressure and of temperature are still further shown in the coefficients of absorption of ammonia in water ascertained by Roscoe and Dittmar. The weight in grammes of ammonia absorbed by 1 gramme of water at 0° C. under variation of direct pressure expressed in metres of mercury was :—

At 0·01 m.=0·044 gram. ; at 0·70 m.=0·840 grm ; at 1·00 m.=1·037 grm. ; at 1·50 m.=1·526 grm. ; and at 2·0 m.=2·195 grm.

Under a constant barometric pressure of 0·76 m. the quantity absorbed under variation of temperature was at 0° C.=0·875 grm.; at 24° C.=0·474 grm.; and at 56° C.=0·186 grm.

Limits of Pressure used.—Roscoe has remarked that the experiments which have been made to verify the law of pressures have been applied, not so much to the determination of the exactitude of the law under high pressures, as to the exemplification of the truth of the law of partial pressures. Thus the solubility of carbonic acid under varying pressures has only been examined by Bunsen between the limits of 523 and 725 millimetres of mercury, whilst Henry employed a pressure of 1·4 metres of mercury.

The limits of pressure, therefore, beyond which gases do not obey the law of pressure have not as yet been experimentally ascertained in many cases. The law, it appears, is not strictly applicable in the case of the more soluble gases within ranges of pressure varying from 0 to 2 atmospheres. Experiments made in Sir H. Roscoe's laboratory showed that under direct variation of pressure of from 0·050 to 2·5 metres of mercury, the quantity of ammonia dissolved in water at all temperatures below 100° C. is not directly proportional to the pressure; but that the deviation becomes less as the temperature increases, until at 100° C. the law of Dalton holds good.

Effects of Mixture.—An admixture of different gases has also been found to affect the degree of solubility of both in water, so that the liquid does not dissolve so much of any one of the gases as it would have done if that gas alone had been present. The presence, therefore, of a foreign gas acts as the equivalent of a direct diminution of pressure.

Action of Water Vapour.—Roscoe has also noted the important fact that "the vapour of water acts precisely as a foreign gas would do in reducing the partial pressures; hence in all the calculations of the absorption-coefficients of gases in liquids determined chemically, the vapour of water present in the atmosphere of otherwise pure gas existing above the liquid must be regarded as a foreign gas, which therefore alters the pressure on the absorbed gases. This consideration has been attended to in but few of the chemical determinations yet made of the more soluble gases."

Conditions of Escape of Gases.—The gases which are absorbed

in a liquid in accordance with Dalton's law are completely liberated from that liquid when the conditions are such that the pressure on the absorbed gases is reduced to zero. This result may be produced in either of the following ways: (1) By actually removing all pressure, except that of the tension of the liquid, by evacuation under the receiver of an air-pump; (2) by placing the saturated liquid in an atmosphere of a gas different from any of those absorbed; (3) by bringing the liquid to the boiling point and continuing the ebullition; and (4) by passing a foreign gas or vapour through the liquid—this last being, as Roscoe says, equivalent to boiling.

Gases are also set free on the solidification of liquids which have absorbed them, but that does not bear upon their action on steam boilers except as also disproving the "liquid" gas theory.

These facts, however, show that Mr. Norris's[1] deductions as to the presence of gases in boilers under high pressures of steam are not well founded, and his theory of their presence in layers above the water cannot be upheld, on account of the laws of diffusion. Apart from the fact that no investigations on this subject have as yet been undertaken at anything like the pressures now employed in steam boilers, where such pressures are accompanied by a considerable rise in temperature, the ascertained result that the vapour of water acts as a foreign gas, would prove that all other gases must be expelled from the water of a boiler under steam. No doubt the iron or steel of the boiler may be hot before the last traces of the gases which water holds absorbed are set free, and so far the power of these gases to act chemically on the metal may be intensified, but it seems certain that these gases cannot be retained there whilst the boiler is at work. It is certain that they enter in the water with which the boiler is filled at starting, and that, unless precautions are taken, fresh quantities may return to the boiler with the feed-water, even though it be produced from condensed steam.

Rate of Absorption.—But here we are without data to guide us as to the quantity which is likely thus to be readmitted, because there are no experimental data available to show the *rate* at which gases are absorbed by liquids under varying conditions of temperature and pressure. The *quantity* absorbed

[1] Trans. Inst. Naval Architects, Vol. xxiii., pp. 154–158.

has been investigated, and it has been found that rain water, which is necessarily the purest of natural waters, contains in one gallon about 7 cubic inches of gas, containing from 20 to 30 per cent. of oxygen, 60 to 70 per cent. of nitrogen, and 5 to 10 per cent. ot carbonic acid. The water of Loch Katrine has been found to contain 7 to 8 cubic inches of gas to the gallon, of which about 3 cubic inches are oxygen. It will be noticed that the proportions in which the various gases exist in water are not the same as their proportions in the atmosphere, but they are in accordance with the relation existing between the coefficients of absorption of these gases in water and their percentage quantities in the atmosphere. It has been found that sea-water holds in solution a larger proportion of carbonic acid than fresh water does, and this has been shown by J. Y. Buchanan to be due to the sulphates which sea-water holds also in solution. (See Appendix III., pp. 611–626.)

As to how long it takes for water to absorb a given quantity of gas, we have as yet no certain data. Judging from the quantity of oxygen absorbed by the blood and the limited time of contact between the gas and the liquid in the process of respiration, it is probable that absorption is a very rapid process. It is, however, unsafe to draw any rigid parallel between blood and water, inasmuch as the action in the case of the blood is not merely a chemical one, but is complicated by the fact that it is an organic action, and we have no equivalent in physics for vital energy.

More nearly allied to our subject is the absorption of gases in the manufacture of aërated waters, but even from this source there is little information to be derived. The absorption of gas in this manufacture takes place under considerable pressure, with the assistance of a low temperature and more or less agitation of the liquid. Moreover, as it is desired to have waters fully charged with gas, some little time is always allowed to elapse before the exposure of the water to the pressure of gas terminates by the operation of bottling. In using the domestic gazogene also, it is always necessary to allow an interval of one to two hours after the operation of charging before properly aërated water can be obtained. But, here again, we are dealing with water which is to be so fully charged with gas under pressure that it will effervesce on exposure to the atmosphere. The presumption is that the amount of gas which water will hold

at atmospheric pressure is absorbed very rapidly. A simple experiment throws light on this point. Let a glass tube half filled with water be sealed up by means of the blow-pipe whilst the water it contains is boiling and steam is issuing. When cold, the metallic click of the "water hammer" will show that the water and the tube are deprived of air—there is a vacuum in the tube. Now let the sealed end of the tube be opened under the surface of ordinary drinking water in a glass vessel, and a very interesting phenomenon will be witnessed. It might be supposed that the water from the outside would at once rush into the tube to fill up the vacuous space, but that does not happen. Instead of that, the water in the glass vessel suddenly becomes violently effervescent, bubbles of air appearing in all portions of it and rushing in every direction and even downwards to the unsealed end of the tube, into which no water enters until a state of equilibrium has apparently been established between it and the water outside it in the matter of the gas contained by each. Thereupon, the water rushes in and completely fills up the tube. All this takes place in a few seconds, and it is proof of the rapidity with which absorption of gas can take place.

Effects of Temperature and Pressure.—It was discovered by Mr. R. Mallet that corrosion proceeds faster in fresh water which contains air, or is in contact with air, at temperatures of 175° to about 190° F. than at atmospheric temperatures, and that in heating such water up to 212°, air is evolved from it most freely at 190° to 195° F., so that there is a direct relation between the rapidity of corrosion and the liberation of air. Mr. Mallett held that the rapidity of corrosion is in the direct ratio of the volume of air set free at any given temperature, because the attraction of the water for the air being destroyed, the air is then free to attack the metal. This observation also serves, to some extent, to illustrate the part played in boiler corrosion by the high temperatures which are usually present. It is well known that chemical affinity is directly affected by temperature, so that some substances which are inert towards one another in the cold, or at ordinary atmospheric temperature, produce active reactions when heated in contact. In general also, chemical action which exists at ordinary temperature is intensified by elevation of temperature.

Increase of pressure—sometimes even without addition of

heat—also produces active chemical action in some cases. We have an instance of this in the mutual decomposition of the magnesia salts and carbonate of lime in sea-water, which is referred to at page 613 of Appendix III.

Influence of Points.—There is a natural phenomenon, which without doubt exerts some influence upon the direction in which corrosive action is developed, and that is the effect produced by points on the metal surfaces. It is well known that if water be boiled in a vessel having a perfectly smooth and clean inside surface the steam does not rise in a steady flow of bubbles, but is produced spasmodically and leaves the surface in sudden, violent and intermittent outbursts. To cure this violent action it is sometimes necessary to introduce into the vessel a little fine sand, the grains of which at once act as nuclei for the formation and escape of steam bubbles, which rise from them in a quiet and continuous stream. A similar effect is seen where little grains even of cork are floating in an effervescing liquid—the floating specks are points at which the bubbles of gas are seen to form and from which they escape.

The discharge of electricity[1] into or through a medium offering some resistance is also determined from points, and this is clearly analogous to the flow of steam or heat noticed above.

Such phenomena render it easy to understand how[2] "the rusting of the purest iron in the form of the most uniform or even polished surfaces of a plate, always initiates at points." These may spread and finally coalesce or the action may proceed more rapidly into the plate than over its surface, in which latter case we have that form of corrosion called "pitting," or, as in R. Mallet's papers, according to French chemists, "tubercular corrosion." "Even were the iron itself perfectly homogeneous," remarked Mr. Mallet, "rust would set in thus at points, for the action is determined to any point touched by another solid, which may be a neutral one (chemically), such as glass, or porcelain, or wood."

Non-uniformity of Texture.—Microscopical examinations of steel and iron, such as those of Dr. Sorby,[3] Professor Roberts-

[1] See Min. Proc. Inst. C. E., Vol. cxv., p. 484.

[2] Trans. Inst. N.A., Vol. xiii., p. 96.

[3] Jour. Iron and Steel Inst., Vol. i., 1887, p. 255; Min. Proc. Inst. C.E., xcv., 144; Jour. Soc. of Arts, Oct. 29, 1897.

Austen, Professor Arnold, and others, have revealed the fact that there is complexity of structure in the finest of such metals, so that there need be no difficulty in our perceiving why the chemical action of corrosion begins at points, even when there is no speck of mill scale or of slag present at or near the surface. The presence of a high temperature intensifies such action, and this of itself would be enough to show that the opinion frequently expressed, that "pitting must be least where the water circulation is greatest," must be wrong, as also the experience of pitting in the boilers of the s.s. "Propontis" and in other water-tube boilers, has repeatedly shown. In these cases the pitting has been greatest in the small tubes or surfaces nearest to the fire, the formation of steam and movement of the water being greatest there also.

Thinness.—Another fact was noticed by Mallet,[1] the accuracy of which experience with boilers has frequently confirmed, viz., that thin material corrodes proportionately faster than metal in thicker pieces. The rapidity with which the thin tubes of water-tube and other boilers have often been eaten through has been a source of surprise to those who did not understand the nature of the action taking place.

Effects of Oils.—The action and effects of oily matters, and their share in promoting corrosion, have been the subject of all shades of opinion, from the incredulity which has denied the possibility of their producing any action, to the dogmatism which has insisted that all corrosive action must be due to them. There are, of course, intermediate shades of opinion which display a more intelligent acquaintance with the facts of the case, and there is no doubt that different instances of boiler corrosion have furnished evidence of variation in the extent to which the action of oils may proceed.

It is at once apparent that we must have widely different groups of phenomena according as we are dealing either with tallow or animal and vegetable oils on the one hand, or with mineral oils on the other. The fats and oils of the one class have as the basis of their constitution, palmitic, oleic, and stearic acids, into which (with glycerine) they can be broken up by the action of heat, and all the more readily in presence of the

[1] See Report, No. 2, p. 236.

alkaline earths, such as lime, potash, or soda. Such decomposition would take place partly in the cylinders of the steam engine, but more extensively in the boiler, where saponification would be possible.

Mineral lubricating oils consist of hydro-carbon compounds, whose specific gravity ranges[1] from ·865 to about ·910, probably anthracene, chrysene, pyrene, etc. They are not liable to any such decomposition as can take place with oils and fats of the first class, but may be volatilised at a high temperature, or partially volatilised and partly reduced to a deposit of solid carbonaceous material.

These two classes of lubricants should not be confounded, but it frequently appears in papers on boiler corrosion that there is some confusion regarding them existing in the minds of engineers. Perhaps the reason of this is to be found in the fact which was insisted upon by Mr. J. B. Dodds, in the paper referred to (p. 325, *ante*), that in commerce the so-called mineral lubricating oil, or "cylinder oil," is seldom to be obtained pure, but is frequently adulterated with vegetable and animal oils. Some analyses[2] seem to bear this out. If so, the remedy is simple, for there should be no difficulty nowadays in buying oil according to a guaranteed analysis, or in analysing a specimen of the material which is sold and delivered for pure mineral lubricating oil.

The action of animal and vegetable oils in connection with boiler corrosion has frequently been exemplified.

In Appendix III. (pages 618 and 619), and in the paper by Mr. Jas. Gilchrist, referred to in the same appendix (page 623), there are details given. Other cases are reported by Mr. H. Hallett, Mr. Sinclair Couper and Mr. J. B. Dodds in the papers referred to (p. 325, *ante*).

Undecomposed grease, unless arrested by filtering, can carry particles of brass, copper, or other foreign material into the boiler, adding to the elements of danger there.

The fatty acids in contact with brass and copper undoubtedly corrode these metals, so that particles of copper separated by attrition, or chemical action, or both, have often been carried

[1] See a Manualette of Destructive Distillation, by E. J. Mills, D.Sc., F.R.S.

[2] Trans. Inst. E. and S. in Scotland, Vol. xl., pp. 103, 104.

into boilers. The fact that Mr. Weston[1] could not find a trace of copper *in solution* in the water of a boiler furnishes no evidence to the contrary, because any salt of copper formed in such circumstances would be quickly decomposed by electrolysis, and therefore the proper place in which to look for the presence of copper would be in the *solid* deposits of the boiler. In such deposits traces of copper have frequently been found[2] by analysis.

When a soapy emulsion, due to the presence of oil, has not been formed in boilers, producing the evils of priming, the soap resulting from the saponification of oil or grease has been found to form first a scum on the water surface and afterwards, by becoming loaded with mineral matters and sinking in pieces, a scale on the heating or other surfaces of the boiler promoting both corrosion and overheating.

Remedy.—The remedy for all this is to use only pure mineral oil for lubricating cylinders, piston rods, and pumps in both main and feed engines.

The possibilities of damage from this oil, if it is pure, are few, and are practically confined to the formation of a coating or deposit on the heating surfaces of the boiler. Where the surfaces become covered with the oil alone the chances of overheating are small, as the experiments recorded in Chapter IV. prove. It is, however, possible to have the oil combined mechanically with solid particles, as has been pointed out by Professor Lewes,[3] according to an action familiar to chemists in connection with precipitation and filtration (see Appendix III., p. 619), and in such cases the chances of damage from the deposit causing overheating are much more serious. The entrance of oil into the boiler is probably not entirely prevented, even by the use of filters, for Professor Lewes has shown by an interesting experiment that a pure mineral lubricant called "Valvoline," having a specific gravity of ·889 and boiling at 371° C. (or 699° F.), was carried over by a current of steam at a much lower temperature than is common in marine boilers. "A retort containing valvoline was carefully heated over a sand-bath, its temperature being ascertained by a thermometer, and

[1] Trans. I. N. A., Vol. xxiii., p. 153.

[2] Trans. Inst. E. and S. in Scotland, Vol. xlii., p. 10, Part v., and Vol. xl., p. 52.

[3] Trans. Inst. N. A., 1891.

steam was then blown through it, with the result that at 248° F. or 120° C.,[1] the steam became 'greasy' and the oil commenced to pass over with it." This of itself does not, of course, explain how the oil gets into a marine boiler, because, as a matter of fact, no steam, either "greasy" or not greasy, is passed *into* that vessel. But the experiment shows that the oil may be, at a comparatively high temperature, readily separated by steam into extremely fine particles which may pass along with the feed water through a filter, especially if the filtering medium has become slightly oily on the surface. Under these circumstances a milky appearance in the water would show the presence of oil, but such milkiness, if due to oil, is readily tested by the addition of ether, which clears it.

There is no reason, however, why the admission of solids to the boiler should not be entirely prevented. Now that feeding with sea-water is abolished in all good marine practice, and the loss of water during a voyage is made up by the use of evaporators or distilling apparatus, whilst all the feed-water passes through a filter such as those shown in Figs. 142, 143, 144, before reaching the boiler, we have only the preliminary filling up with natural fresh water to consider as a possible breach in the defence of the boiler. In this case, if water of the purity of rain water cannot be obtained for filling up the boiler before a voyage, any salts of lime, soda or magnesia which the water which is employed contains, should be removed by a preliminary precipitation and filtration, before the water is admitted to the boiler.[2] Thereafter and during work, as we have seen, the entrance of fresh quantities of solids can be prevented.

It is not likely that, where filters are used, and economy in the use of lubricating oil is practised, a quantity of oil can pass into the boilers sufficient to form an oily scum on the surface of the water. But if, through some defect in the filter, that result should occur, it will cause trouble in the working of the boiler, and should be removed by blowing off.

[1] This temperature corresponds to a steam pressure of only 30 lbs. per square inch.

[2] On this point consult Report XV., "On the Purification of the Feed-water of Locomotives," presented by J. A. F. Aspinall to the International Railway Congress. Sixth session. Paris, 1900.

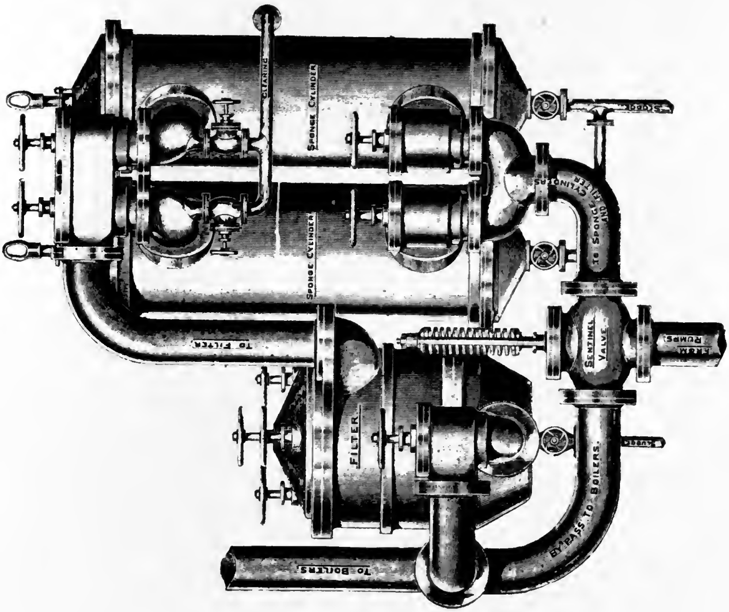


FIG. 143.

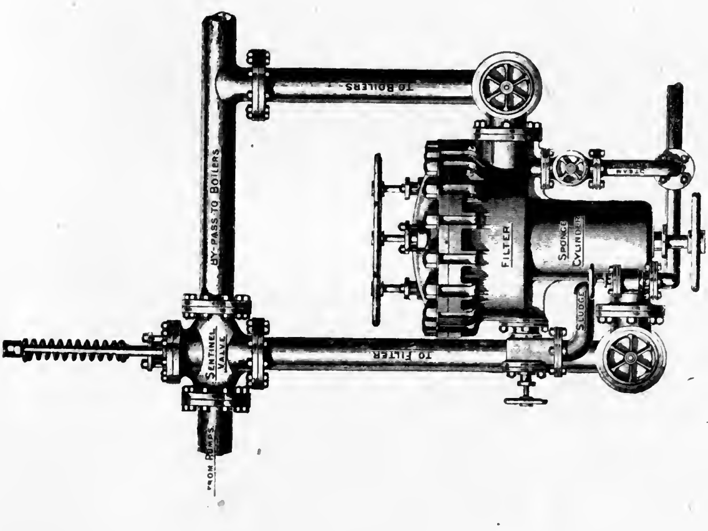


FIG. 142.

Action of Magnesic Chloride.—The disuse of sea-water for feeding or for making up the feed-water in marine boilers has removed several causes of destructive action, such as the decomposition of magnesic chloride and the presence of an additional quantity of carbon-dioxide liberated from sea-water,

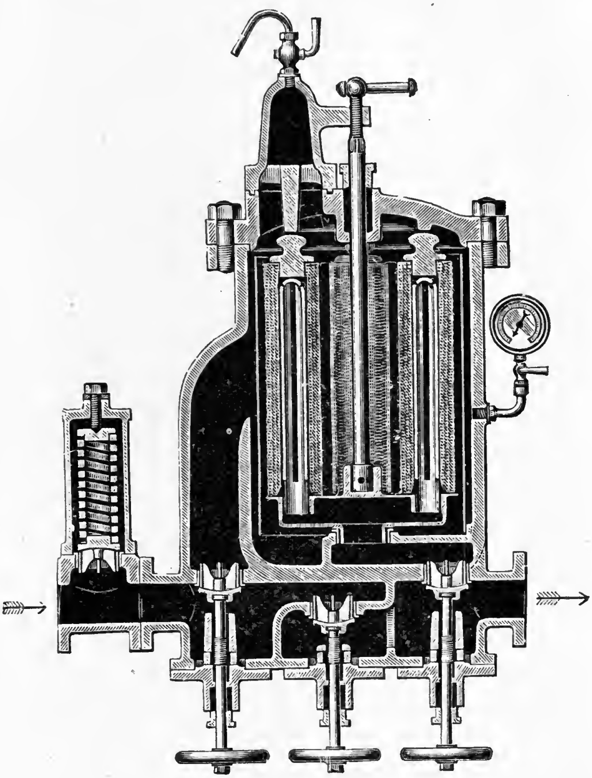


FIG. 144.

which are noticed in Appendix III.[1] and do not need to be further dealt with. But it may be remarked that as regards the decomposition of magnesic chloride and resulting reactions, hasty inferences have frequently obstructed a clear understanding of the matter. It was inferred that if by the decomposition

[1] See also paper by J. B. Dodds, in Trans. N. E. Coast Inst. of Engineers, Vol. v., p. 195.

referred to, hydrochloric acid was set free, the presence of this acid ought to be indicated by acidity in the water of the boiler ; whereas its action on the iron must always have been practically simultaneous with its liberation from the magnesic chloride, so that instead of the water showing an acid reaction it was more likely to become alkaline by neutralisation of the hydrochloric acid and accumulation of magnesic oxide. It was also argued that if the iron were attacked by hydrochloric acid, chloride of iron ought to appear in the deposits found in boilers. But that objection, like other arguments, was anticipated some years before it was made, by the paper reprinted in Appendix III. (p. 625) in the statement that oxide, and not chloride, of iron finally results from the action. This was also subsequently demonstrated by Mr. J. B. Dobbs (in Trans. N. E. Coast Inst. of Engineers and Shipbuilders, Vol. v., pp. 196, 197, 247). Due weight was, moreover, seldom given to the fact of the presence of a larger quantity of carbon dioxide in salt than in fresh water, a great part of this carbon dioxide being liberated from the sea-water by the mere separation of the sulphates which it holds in solution. These various phenomena, however, explain how chemical action has been found to proceed more rapidly in boilers which have been partly fed with sea-water, than in those from which sea-water is carefully excluded, and they demonstrate how necessary it is that in all marine boilers the feed should be made up with distilled water alone.

It no doubt follows from this that we must expect to find corrosion at work in distilling boilers or apparatus used to produce distilled from sea-water. The action of air and carbon dioxide also show that corrosion may be expected in feed-heaters which receive the feed-water either cold or comparatively cold, where no effort has been made to keep it denuded of air. Where such feed-water is delivered into boilers direct, without interposition of a feed-heater, the parts of the boiler coming first into contact with this water, on its temperature being raised, must also be exposed to corrosive actions.

Delivering the feed into the steam space is no doubt the safest method where air is present in the water, from the point of view of corrosion, but it is not good in its effects on circulation, as Mr.

Blechynden's experiments prove[1]; nor is it economical from the point of view of heat transmission.

It is undoubtedly better to have an evaporator or feed heater liable to corrosion separate from the boiler, than to expose any part of the boiler to this action, and hence Mr. Yarrow's plan of making some of the tubes of his boiler do the duty of a feed-heater may lead to difficulties which more than counterbalance any economy of heat obtained by this arrangement.[2]

Protective Measures.—Amongst the means employed for the protection of boiler surfaces from corrosion, the action and effect of zinc have often been greatly over-estimated. In fresh water zinc has little protective power over wrought iron considered electro-chemically, and in sea-water it is readily oxidised by decomposition taking place in the salts which that water contains. With regard to the action in cold water, Mr. Mallet[3] wrote that, "zinc is so slightly electro-positive to iron that its protective power is nearly destroyed whenever a few spots of rust have formed anywhere upon the iron with which it is in contact, the peroxide acting as an acid towards its own base in both fresh and sea-water. In the latter the surface of the zinc gets covered with a hard crystalline coat of hydrated oxide and of calc-spar, which retards or prevents its further corrosion, and thus permits the iron to corrode." In boiling water the action proceeds much farther, and progesses rapidly, so that the zinc is often quickly reduced throughout. Moreover, as commercial zinc is seldom pure, there are causes of reaction in the constitution of the metal itself which aid in its disintegration ; a result which amalgamating its surface with mercury cannot prevent.

It is probable that the principal service rendered by zinc in boilers has been to provide a material acted upon more readily than the iron by the acids set free by the decomposition of animal and vegetable oils, and by the oxygen and carbon dioxide liberated on boiling the water. Mr. Mallet stated that an alloy of 23 parts of zinc and 8 parts of copper preserves cast iron from corrosion in cold water, and does not waste itself, but it is difficult to understand how such a result could be obtained. Protective action has been claimed for devices such as one

[1] See Chap. V., p. 243, *ante*. [2] See Chap. V., p. 234, *ante*.
[3] British Association Reports, 1843, p. 20.

called the "Electrogen," which aimed at producing a galvanic current in such relation to the iron as constituted it the negative element of the couple. If this really has a preservative effect, probably the same result could be more fully realised by passing a small current from a dynamo machine through the boiler. At any rate this is worth investigation in these days in which so many steamers are fitted with electric-lighting machinery.

Protective Coatings.—Efforts have also been made, with some degree of success, to protect the iron of boilers by forming a protecting coating on the boiler surfaces, and with a similar object it has also been proposed to render the water innocuous to iron by chemical means. With regard to the former of these plans, there are two methods by which a permanent covering, impervious to corrosive action, can be formed. These are the process invented by Professor Barff and the method suggested by the author of this work.

In Barff's[1] process a thin adherent coating of magnetic oxide is formed on the iron by the decomposition of steam in contact with the metal at a temperature of 500° F., whilst in that of the author[2] a similar covering composed of calcium sulphate and magnesium hydrate is first deposited from fresh water and subsequently hardened by heat. The addition of lime preparations to the water, in the manner suggested by the author, would render the water "non-exciting," as Mr. J. B. Dodds[3] has pointed out, and to produce the same result he proposed the use, alternatively, of a basic solution of zinc.

When not in use boilers should be filled to the top of the steam space with hot water which has been boiled to free it from air, and the boiler should then be hermetically closed and kept in this condition until it is required for work. Lime may be added to this water or placed in the boiler, but this, though desirable, should not be necessary if the boiler has been thoroughly cleansed before being filled up with the water.

"Another method of preserving a boiler not in use is to empty it and clean it thoroughly, then close all the manhole doors and other openings except one at the bottom, through

[1] See Jour. of Soc. of Arts, February 14, 1877. Jour. Iron and Steel Inst. Vol. i., 1881, p. 166; Vol. ii., 1888, p. 280.

[2] See Appendix III., pp. 627, 634.

[3] Trans. N. E. Coast Inst. of Engineers, Vol. v., pp. 198-200.

which a small stove full of burning coke is put in, and then the bottom door is closed quickly." The object of these methods is, of course, to exclude moist air as thoroughly as possible.

On a review of the subject it is apparent that in good practice the following points should be observed :—

1. The metal of which boilers are constructed should be as homogeneous as possible in composition and texture. It should be well worked so as to be fibrous rather than crystalline in texture, and should not be punched or worked at a low heat. It should be well annealed so as to remove all effects of local stresses and to bring the texture to a uniform condition.
2. All mill scale and dirt should be removed from the surfaces, which should also be kept as free as possible from oil.
3. All gases should be removed from the water.
4. No sea-water should be admitted, and all feed-water should be made up with distilled water.
5. All feed-water should be passed through a good filter.
6. The feed-water should be heated in feed-heaters which are separate in construction from the boiler.
7. The interior surfaces of the boiler should be covered by a thin protective coating, or the water should be treated chemically as above.
8. No vegetable or animal oil should be used in any engines connected in any way with the boiler.
9. When not in use boilers should be carefully protected from deterioration by one of the methods described.

CHAPTER VIII.

HISTORICAL SKETCH OF BOILER DESIGNS.

IN the production of steam for other than domestic purposes various kinds of vessels and modes of operating have been tried. The more ancient forms of boilers appear to modern eyes somewhat grotesque, and it is certain that they were not adapted for continuous work of long endurance. They were, however, not subjected to any great stress of work. An archaic form has been described by a writer in *Engineering* of 11th January, 1895, where an illustration of it appears.[1] It was an urn-shaped vessel discovered at Pompeii.

Others will be found in the older works containing a historical account of the development of the steam engine, such as the writings of Stuart, Farey, and Tredgold.

The earliest practicable boilers seem to have been spherical or oval (sometimes called "ovoid") vessels, but after a time flat surfaces were introduced in the "waggon" and similar forms, whilst other designs, more suited to the production of steam of some degree of pressure above that of the atmosphere, soon began to appear.

Methods of Raising Steam.—In the various methods of raising steam which have been practised, the following arrangements have been used :—

1. A compact body of water enclosed in a vessel of spherical, cylindrical, oblong, or other form, and heated from the outside, either without or with internal flues or passages. This is the tank or shell boiler, which has assumed many shapes, with plain or spiral flues and even with inverted furnaces, the latest developments of which are the so-called "Scotch" cylindrical or drum boiler, the Lancashire boiler, and the locomotive boilers.
2. Small quantities of water projected successively on the inner surfaces of a vessel kept at a high temperature by

[1] See also "Les Chaudieres Marines," by M. de Chasseloup-Laubat. Paris : 1897.

fire applied to the outside, so that the water is wholly and instantaneously converted into steam on coming into contact with the heated surface. This applies to all the boilers which make steam by flashing the water into steam, whatever may be the actual design of the boiler. This method was first suggested by John Payne in his patent of 1736 (No. 555) and paper to the Royal Society in 1747, and has been subsequently tried with a variety of forms of boiler.

3. Mechanical means for stirring or agitating the water, proposed by Sutton Thomas Wood in 1784 (No. 1447), "to expose a greater surface of the heated liquor to the rarer medium ; and by opening the pores of the water to cause the weaker steam to be freed from that weight or pressure that before confined it, and enable it to rise and mix itself with the steam above the surface of the liquor and thereby increase the quantity."
4. Heating surfaces so disposed that the water, instead of being in a compact mass, is broken up into thin sheets, so that comparatively small quantities are acted upon by the heat. There is no doubt that this is a main principle of all sectional and water-tube boilers ; but although Wm. Blakey, in 1766-1774 (No. 848), and James Rumsey in 1788 (No. 1673) had introduced two forms of these, it is probable they had in view merely the question of steam pressure and not that of rapid steam generation. In that case the merit of perceiving the effect of sub-division on steam generation would rest with Matthew Pitts, who in 1793 (No. 1943) announced that, though "the received opinion" at that time was that "to obtain steam a compact body of water was required," and "where a great body of steam is wanted a great body of boiling water is necessary," yet he had "found from experience that a large quantity of steam can be obtained by having in use a small quantity of water disposed so as to cover a large surface ; and the quantity of the steam is in proportion to the extent of surface and strength of heat."

The value of sub-division in view of safety from explosion seems first to have been set forth by Aaron Manby in his patent of 1821 (No. 4558).

5. *Revolving Boilers.*—These apparently aim at the same result as do the arrangements in No. 3, although reversing the order of procedure. The result really aimed at in such devices we now understand to be increasing the efficiency of the heating surface. "The pores of the water" were the point of attack in olden time, but now it is the transmission of heat to and through the boiler surfaces to the water. It is not unlikely that the idea of revolving boilers may have been suggested by such engines as Amonton's fire-wheel (of 1699), described and illustrated in Stuart's "Descriptive History of the Steam Engine," or by some other form of the rotary engine, the idea of which was popular in very early days.

6. Another method of generating steam, which had some promise of success from more than one point of view, was suggested as early as 1821 by Aaron Manby in his patent No. 4558. This consisted in heating a comparatively small quantity of oil, or some other liquid capable of being highly heated without undergoing decomposition, and causing this heated substance to circulate through tubes or passages which were in contact with water. This plan was revived as lately as 1876 (No. 4235) in Barron's boiler,[1] but the temperatures reached by the modern use of high pressures practically remove it from the list of methods of working now available. In a modification of this method, applicable to boilers in which small quantities of water are successively flashed into steam, a fusible alloy was employed as the medium for transmitting the heat to the boiler surfaces.

[See also J. C. Gamble (No. 5327 of 1826) and Beale and Porter (No. 5609 of 1828)].

Jacob Perkins' method might be considered as a distinct system, although it was allied in a certain degree to that of the flash boilers.

Sectional Steam Boilers.—In tracing the history of the introduction of sectional or water-tube boilers, some writers have

[1] See Flannery on "The Construction of Steam Boilers for High Pressures. Min. Proc. Inst. C.E., Vol. liv., p. 123.

gone for a starting-point to Hero's "Spiritalia seu Pneumatica,"[1] on account of its containing two designs of automatic apparatus (composed partly of vertical tubes) in which a small quantity of steam when formed was used to blow up a fire placed on a grate on the top of the apparatus. These were not, properly speaking, boilers—if for no other reason, because the steam could perform no useful work outside of the apparatus itself—but were merely two forms of the philosophical toys or wonder-working mechanisms which were proposed or used to impress the superstitious fancy of an ignorant people. Small differences in the temperature and pressure of air and water were the only forces employed in them, but these were used to produce often mysterious-looking results.

Apparently the earliest design of a sectional or water-tube boiler on record is that of Wm. Blakey, who patented in 1766 (No. 848) some improvements on Savery's engine. A high-pressure boiler is referred to in his patent, but according to Stuart[2] the boiler shown in Fig. 145 was not invented by him until 1774.

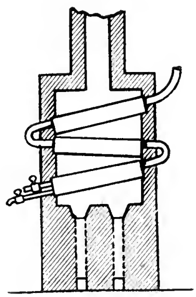


FIG. 145.

The boiler as thus illustrated consisted of water tubes horizontally placed over the fire but inclined at a slight angle alternately to right and left, and connected at their ends by bent pipes, so as to provide, with these end connections, a constantly ascending path for the steam as generated. The tubes were thus coupled together in series, and formed a serpentine coil or flattened spiral, precisely as do later boilers, notably that of Belleville, of which Blakey's may be taken as illustrating a single "element" in a simple form.

A water-tube boiler of different design appears to have been introduced by Fitch and Voight into a small steamboat in America in 1787. This design is represented in Fig. 146, and the boiler consisted of an iron tube coiled backwards and forwards in the combustion space of a furnace formed of brick-

[1] Published in the Collected Works of the Ancient Mathematicians. Paris: 1693. Also Translated into English by Professor Greenwood. London: 1851.

[2] Stuart's Descriptive History of the Steam Engine. London: 1824. The Steam Engine, by D. K. Clark, Vol. ii.

work. Consequently this was, strictly speaking, a coil boiler, and the first of its kind, although, in a general way, all water-tube boilers in which the steam must traverse more than one tube before escaping from the water partake of the nature of coils. James Rumsey claimed that he was the inventor of this boiler, and had a public controversy with Fitch, which it is stated[1] was not altogether favourable to Rumsey. It is admitted, however, that Rumsey began experiments, having in view the application of steam to navigation, in 1774, and in 1786 (according to Professor Thurston) "he succeeded in driving a boat at the rate of four miles an hour against the current of the Potomac at Shepherdstown, West Virginia, in presence of General Washington." This boat was propelled by means of a water-jet, but we are not informed as to the exact design of boiler which was employed in it. Rumsey took out a patent in Britain in 1788 (No. 1673), in which he described more than one form of boiler, the design introduced by Fitch and Voight being one of these, whilst there is no record of a British patent having been obtained by these latter.

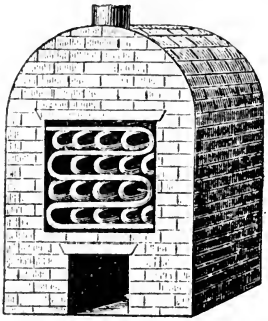


FIG. 146.

The boiler patented in France in 1793 by Barlow, and introduced into a steamboat there some years later by Robert Fulton, a celebrated American engineer, must also rank as one of the early examples of water-tube boiler design. It is represented in Fig. 147, and the illustration shows it to have been constructed of iron tubes stretching horizontally across the fires and having their ends opening into flat rectangular

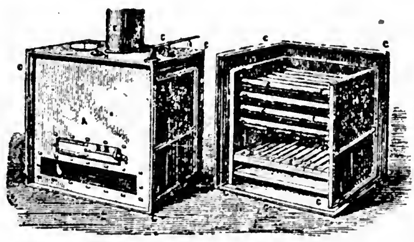


FIG. 147.

[1] A History of the Growth of the Steam Engine, by Professor R. H. Thurston. Vol. xxiv. of the International Scientific Series.

boxes or chambers, each common to all the tubes, and forming a side of the boiler. The use of a flat chamber of such area is a defect noticeable in the design of this and one or two early boilers of the same class, but in later forms it disappears, as "headers" of comparatively small section are introduced. Bariow's boiler[1] is said to be preserved at the Conservatoire des Arts et Métiers in Paris, but there is no record of its design having been introduced into Britain in his name. One of Rumsey's designs in patent No. 1673 of 1788, seems from the description to resemble Barlow's plan.

Teschemacher's Boiler.—The patent of J. R. Teschemacher (No. 1808 of 1791) contains the idea of a film system of evaporation applied to boilers. His boiler was in form a flat rectangular pipe, placed vertically, and containing a series of inclined planes like hollow shelves, on which the water was made to flow downwards in a zig-zag direction from one hot shelf to another. The rectangular pipe was heated externally throughout its entire length if necessary, and communicated with a vertical steam-pipe connected with the various inclined cavities, so that the steam could escape as it was formed.

Whatever the defects of the apparatus, the idea of exposing the water in a thin layer to the action of heat was original and good. It has not often been applied to boilers, but, especially in later years, has become of importance in other evaporating plant, the most modern forms being those of Yaryan and Foster.

Flash Boilers.—The system first suggested by Payne found in early days many followers. The flashing of small quantities of water into steam by sudden contact with very hot metal surfaces was, in fact, as has been remarked elsewhere, a favourite idea with early inventors. John Payne's patent (No. 555 of 1736) did not describe his boiler, but later he gave a description of it in a paper to the Royal Society of London.[2] It appears from that account that his boiler was shaped like a balloon, the middle portion being exposed to the flame and hot gases from a furnace. Inside, a small revolving wheel, like a Barker's wheel, threw the water in spray from its circumference upon the highly heated

[1] See also "Des Machines à Vapeur," by A. Morin and H. Tresca. Hachette and Co. Paris: 1863. Vol. i., p. 253.

[2] See Phil. Trans., 1747, p. 828.

surfaces, on coming into contact with which it was at once converted into steam. Any unevaporated water fell to the bottom of the vessel and was removed by a pump. Subsequent inventors introduced variety in the details, whilst adhering to the main system.

Matthew Pitts and Thos. Strode (No. 1867 of 1792) used an "ovoidal" vessel or chamber having a tube or pipe for water inserted at the top. A small stream of water falling from a height through this pipe splashed into spray which fell on the heated surfaces.

John Dale (No. 1950 of 1793), on the contrary, used a force pump to project a number of small jets of water, hot from a condenser, against the upper portion of a boiler surface kept at nearly a red heat.

Richard Willcox (No. 2493 of 1801) did not describe any special form of apparatus, but seemed to appreciate the fact that it was possible to have the metallic plate heated to such a point that the water might be chemically dissociated.

John Seaward (No. 4356 of 1819) proposed to use a flattened coil of tubes set in a furnace, the first two horizontal lengths forming the roof of the furnace and the others being in the flue space beyond. The water was to be heated in a casing or jacket surrounding the vertical flue, and injected by a force pump into the first tube of the series placed directly over the fireplace. On entering, the water was to strike against the apex of a conical plug so as to be finely sprayed against the sides of the tube.

Sir Wm. Congreve (No. 4593 of 1821) proposed injecting small quantities of boiling water from time to time into a small inverted receiver placed in a melted alloy melting at about 300° F., or fusible metal melting at 200° F. By this arrangement he imagined that a boiler could be dispensed with. Alternately the water was to be injected on the heated alloy in a vessel or chamber. This patent has a better claim to notice in the fact that it contains one of the first suggestions for superheating steam on its progress from the boiler to the cylinder. The true value of superheating was of course not yet known.

John Theodore Paul (No. 4950 of 1824) formed a boiler of a continuous length of copper pipe coiled in the form of two concentric cylinders or spirals slightly conical, the annular space between the two being occupied by the fuel which was to be

fed into it from a pipe or shoot above. The patent set forth that for a two horse-power engine, with a pressure of 150 lbs. per square inch, the copper pipe should be 150 feet long, three-sixteenths of an inch internal diameter, and one-sixteenth in thickness. This might be supposed to be an ordinary coil boiler but for the statement in the patent that the length of pipe should be sufficient that, when heated in its whole length below redness, the water which was forced into it at one end should issue from the other end as steam of the required pressure. The water was to enter at the top of the outside coil, descend it, and then ascend the inner one. There was thus no circulation, in the ordinary sense, in this boiler, but the water, gradually warmed, was to be flashed into steam as soon as it reached a certain point.

John McCurdy (No. 4974 of 1824), a month later, proposed a boiler formed of cast iron tubular chambers, 6 to 12 feet in length and from 5 to 10 inches in the bore, having a small perforated tube or injection barrel extending through the whole length of each. By means of these perforated tubes the water, when forced in by a pump, was sprayed radially throughout the whole length of the chambers and flashed into steam from their hot surfaces.

Wm. Gilman and J. W. Sowerby (No. 5150 of 1825) proposed to spread the water in a thin film over the inner surface of cylindrical boilers by means of the centrifugal action of agitators inside, and J. C. C. Raddatz (No. 5163 of 1825) proposed vertical metallic tubes, closed at the bottom end and coupled to a common chamber above, to be wholly immersed in a bath of fluid tin and lead alloy. A small jet of water, introduced into the top of each tube from a common supply pipe led through the horizontal steam chamber, instantly formed steam by contact with the heated tube.

These, with the boilers proposed by M. S. Boutigny (see No. 786 of 1855) and M. F. Isoard (No. 1637 of 1855), are amongst the most important of the earlier suggestions for that method of working. In more recent years, this system has been more identified with a tubulous form of boiler, or with capillary passages, as in the earlier boilers of Herreshoff and Belleville, and in the boilers of Serpollet in France, De Laval in Sweden, and Simpson and Bodman in England.

Jacob Perkins' System.—Although it was to some extent allied

to the method of making steam by flashing, yet the system proposed by Jacob Perkins (in No. 4732 of 1822, and No. 5477 of 1827) possessed features which entitle it to be regarded as an entirely original one. Perkins' idea was to heat water, in a suitable vessel, to 400° or 500° F., the vessel being quite full of water. Then, by forcing an additional small quantity of water into the vessel by a pump, a corresponding quantity of the superheated water would escape by means of a valve into a steampipe, where it would instantly flash into steam. He first proposed a copper cylindrical vessel of three inches thickness for this process, and afterwards described a boiler composed of small horizontal tubes set like retorts in a furnace, similar horizontal pipes being provided for the steam as formed. Apart from the fact that in his later patent he proposed to pass the steam when formed through water which was not externally heated, and would thus lose heat uselessly, the process of generating steam in that way is not likely to be economical and is not free from objections on the score of practicability.

Practically the same system was repatented by Samuel Roberts on 11th April, 1861 (No. 898).

Woolf's Boiler.—Although Richard Shannon (No. 2212 of 1798) proposed an arrangement of coppers for evaporating, which was also suitable for the construction of boilers and suggests the form of Woolf's boiler, and James Sharples (No. 2576 of 1802) proposed a sectional boiler formed like a wheel, yet the boiler patented by Arthur Woolf (No. 2726 of 1803) was the first practicable water-tube boiler after Blakey's and Rumsey's. Woolf's boiler, Fig. 148, was composed of horizontal water-tubes, placed over a fire parallel to one another and a small distance apart. When nine tubes were employed the fireplace was formed under the first four tubes, then the flame and hot gases were carried along under the fifth, above the sixth, round and under the seventh, round and above the eighth, round and below the ninth, then back by a zig-zag flue in the opposite order to the front of the boiler and then to a chimney placed above. Each

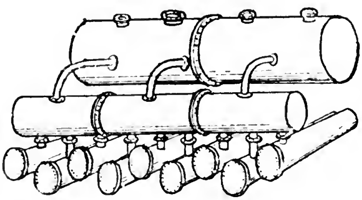


FIG. 148.

horizontal tube was connected by a short vertical tube to a large cylindrical vessel which was placed transversely across the centre of the tubes, and the course of the hot gases was arranged to miss these vertical pipe connections. The water level stood about half way up in the diameter of the upper chamber, the upper half of that vessel forming the steam space.

Cast Iron Boilers.—Woolf's boiler was constructed of cast iron, but this material, although much used for boilers in early days, could not attain an extended use in presence of wrought iron or steel when they became available. It was, however, proposed for the sectional boilers invented by J. McCurdy in 1824 (No. 4974), which was a flash boiler composed of tubular chambers heated on the outside, with concentric perforated tubes for spraying the water within ; of Henrik Zander in 1839 (No. 8 III.), which was a cellular form of boiler ; in the case of the first Babcock and Wilcox boiler ; and in the later water-tube or sectional boilers of Miller, Harrison, Allen, and the Exeter boiler.

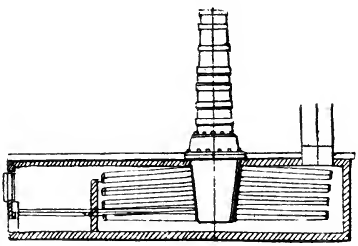


FIG. 149.

Stevens' Boiler.—The boiler made by John C. Stevens, of New York, in 1804, may also, according to the late Mr. Zerah Colburn,[1] have been constructed of cast iron, but the particulars given by Professor Thurston[2] would rather lead to the conclusion that it was formed of copper tubes cast in brass tube plates, one end of the tubes being plugged by caps of cast iron or brass.

Stevens' boiler is shown in Fig. 149. It contained 100 tubes 2 inches in diameter and 18 inches long, each fastened at one end to a central water chamber, the upper part of which formed a steam drum, and plugged at the other end, a bolt passing through each cap and tieing it to the tubeplate.

Stevens' British patent was taken out in 1805 (No. 2855), but does not describe the boiler illustrated.

[1] Proc. Inst. Mech. Engineers, 1864, p. 72.

[2] Hist. of the Steam Engine, p. 266. Trans. of the Inst. E. and S. in Scotland, Vol. 41, p. 62.

Miller's Boiler.—Miller's boiler was undoubtedly a cast iron boiler. It was designed by Mr. Joseph A. Miller, of New York, and was introduced into Britain in 1868, having been described and illustrated in *Engineering* of 4th December and *The Engineer* of 25th December of that year. An account of it was presented to the Institute of Mechanical Engineers in 1871 by Mr. John Laybourne (see Proceedings 1871, p. 263). Its form is shown in

THE AMERICAN SAFETY BOILER.

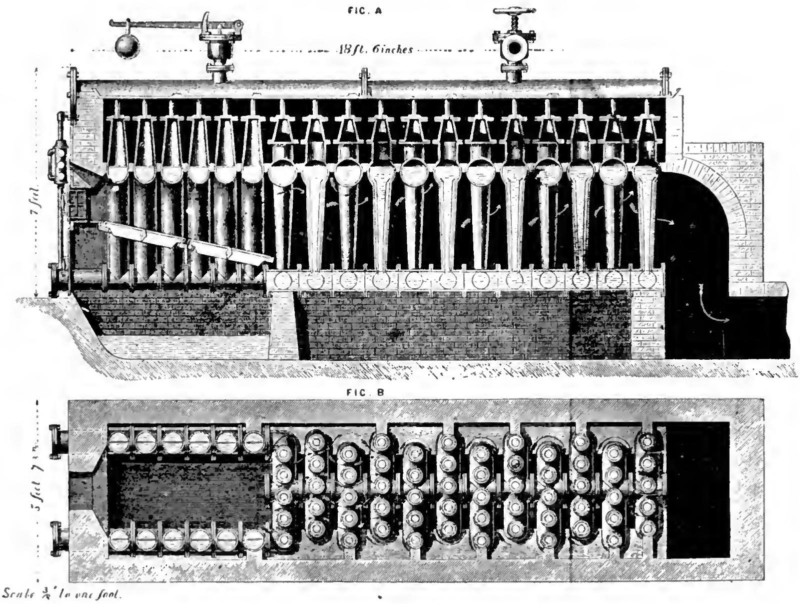


FIG. 150.

Figs. 150 and 151. It was constructed of a number of units in the form of vertical conical tubes connected by transverse horizontal tubes at the bottom and near the top. The fireplace was formed by special units in the shape of a semicircular arch. Circulation of the water was ensured by the insertion of mid-feathers in the furnace units and internal "Perkins" or "Field" tubes in the rear units. Some dimensions and results of work with this boiler will be found in the papers quoted above,

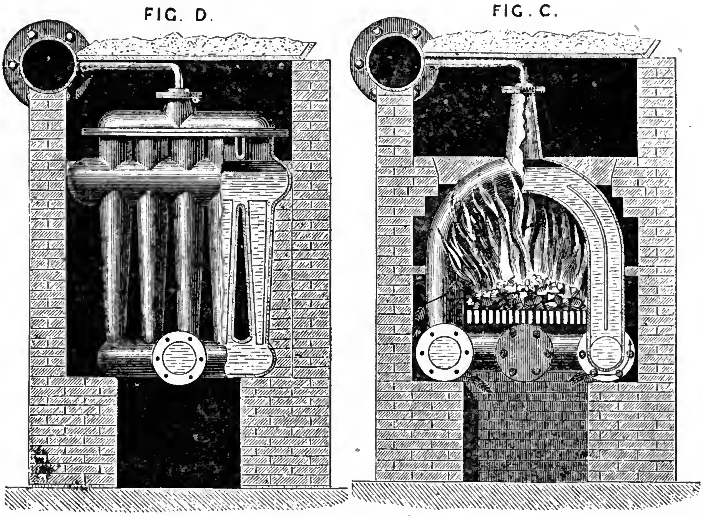


FIG. 151.

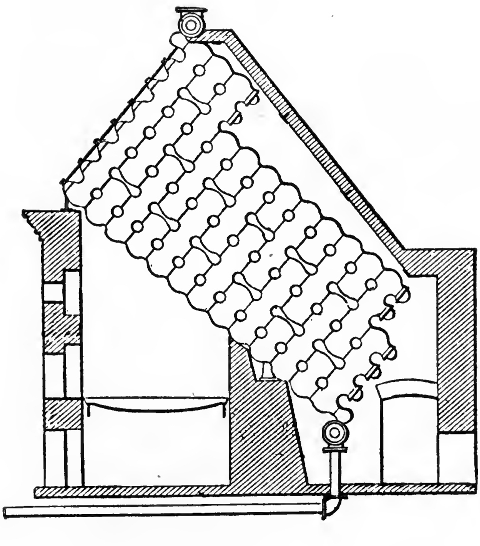


FIG. 152.

and in "The Steam Engine," by the late D. K. Clark (Vol. ii., p. 787).

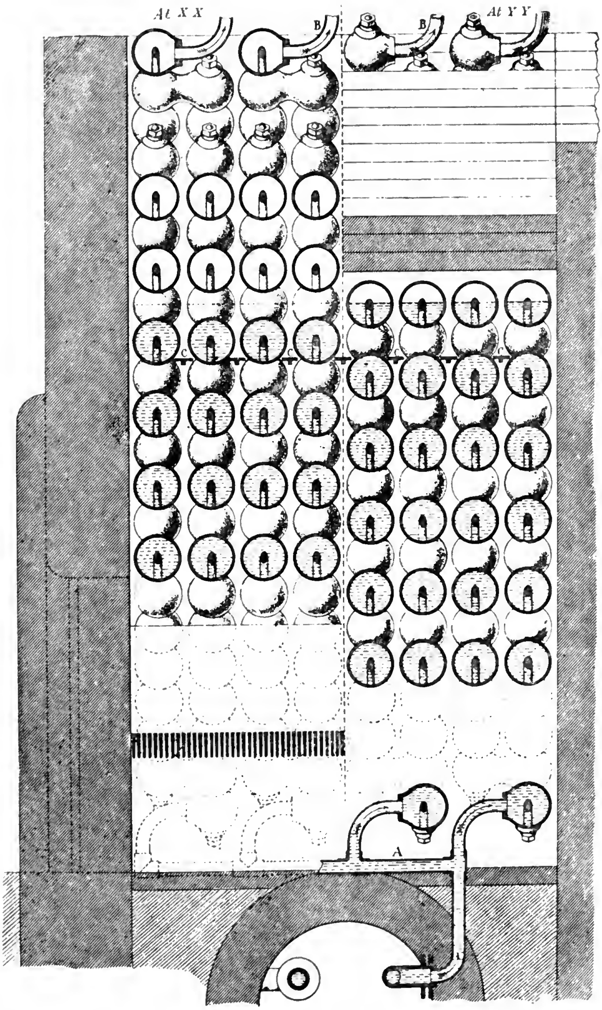


FIG. 153.

Harrison's Boiler.—The boiler designed by Mr. Joseph Harrison, of Philadelphia, U.S.A., is shown in Figs. 152, 153, and 154.

It was formed of hollow cast iron spheres connected by hollow

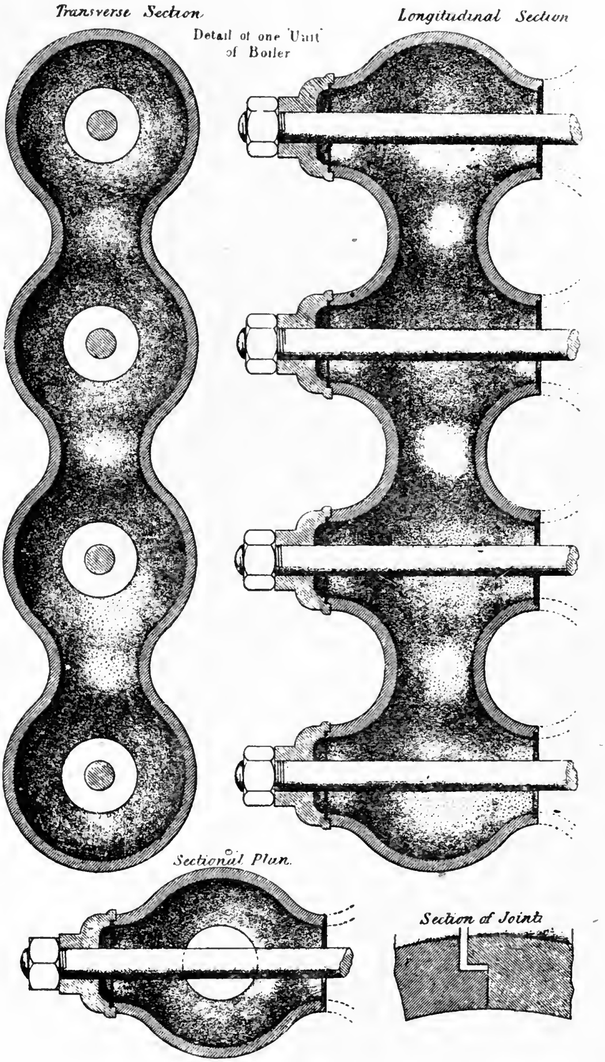


FIG. 154.

necks, each unit casting consisting of four spheres 8 inches external diameter, $\frac{3}{8}$ inch thick, connected by necks with $3\frac{1}{8}$ inches opening,

the various units being secured together by internal bolts of $1\frac{1}{4}$ inch diameter. As described to the Institute of Mechanical Engineers by Mr. Zerah Colburn in 1864 (Proceedings 1864, p. 61) the boiler was set at an angle over the fire, but a later form in which the spheres are arranged vertically is known as the Wharton-Harrison boiler and is illustrated in Fig. 155. Harrison's British patents are 1859 (No. 1970) and 1862 (No.

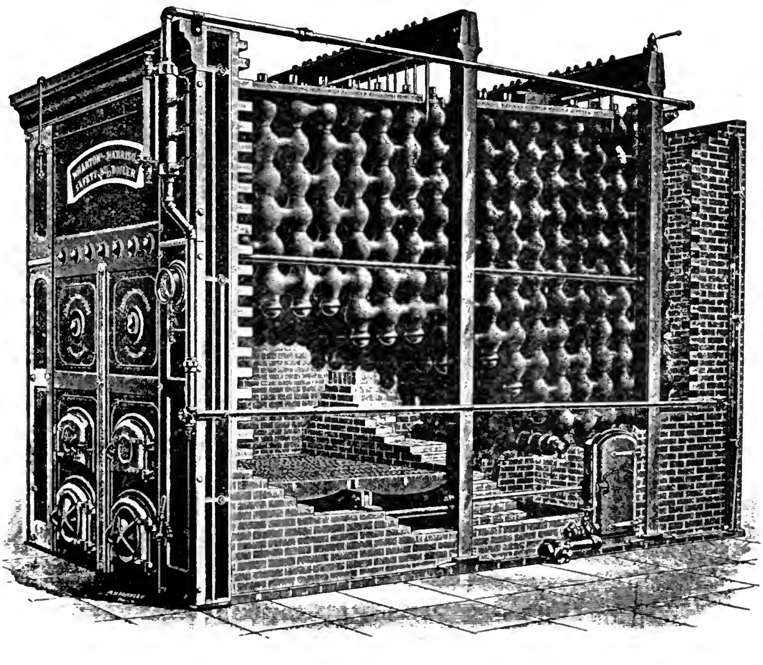


FIG. 155.

1340). Some results of trials of this boiler in competition with other boilers at the International Exhibition at Philadelphia in 1876 will be found in Chapter IX., and in "The Steam Engine," by D. K. Clark (Vol. i., pp. 253-263).

Allen Boiler.—The Allen boiler is also of American origin, and was composed of horizontal cast iron chambers or cylinders from which wrought iron tubes $3\frac{1}{2}$ inches diameter, closed at the bottom ends by screwed caps, depended at a slight angle.

It is represented in Fig. 156. The hanging tubes over the fire are made shorter than those in rear of the furnace in order to form a combustion space. As these tubes were not furnished with internal tubes for circulation, they were hung at an angle towards the back of the furnace in order to favour circulation and separation of the steam from the water. Particulars of the performance of this boiler in the trials at the American Institute Exhibition will be found in Chapter IX.

The *Exeter Boiler*, Fig. 157, consists of rectangular hollow slabs of cast iron, placed in rows across the boiler setting, and forming a series of vertical leaves or chambers pierced with passages for the hot gases. The leaves are connected by small branch pipes passing through the brickwork to a steampipe

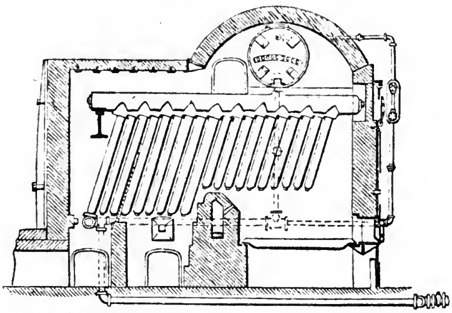


FIG. 156.

above and a feedpipe below. The steam pipes connect with a steam drum placed across the centre of the boiler above the brickwork. The water level stands at about two-thirds of the height of the leaves. This is an American boiler which was tested with others at the International Exhibition, Philadelphia, in 1876. It does not seem to have been widely introduced.

Horizontal Tube Boilers.—The design which employs horizontally placed water tubes—either horizontal or slightly inclined tubes—is, as we have seen, the earliest which was used in the construction of water-tube boilers, and it remains in use till the present day. The modifications of this design are chiefly concerned with the methods by which the ends of the tubes are connected, and these methods broadly divide these boilers into two groups—viz., those in which the tubes in a vertical row are

connected "in series," so that the water and steam must traverse each tube in the row successively, and those which have the tubes coupled "in parallel," where the tubes are supplied with water from a common water chamber, and the steam from each tube can escape directly to the steam chamber without traversing more than a single tube. The former method is illustrated in the boilers of Blakey, Julius Griffith, 1821 (No. 4630), Moses

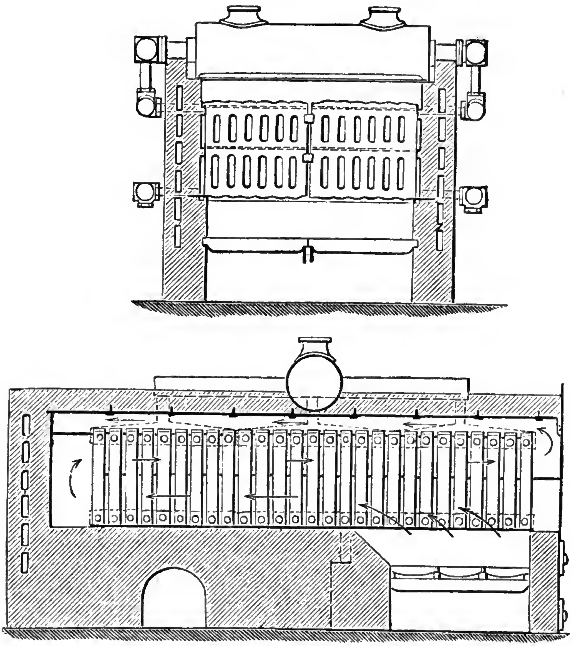


FIG. 157.

Poole, 1829 (No. 5815), Andrew Smith, 1838 (No. 7916), J. F. Belleville, 1852 (No. 725), 1856 (No. 1606), 1860 (No. 155), 1865 (No. 3269), and Martin Benson, 1858 (No. 1903). The latter method finds illustration in the boilers of Rumsey, Barlow, Woolf, and Stevens already mentioned, and in those of Julius Griffith (a later design than that of his patent of 1821), W. H. James, 1832 (No. 6297), Joel Spiller, 1835 (No. 6897), Earl of Dundonald, 1835 (No. 6923), G. H. Moreau, 1842 (No. 9562), which was a boiler similar to Woolf's but made of copper tubes ;

Thos. Lawes, 1851 (No. 13440), who formed channels for the hot gases by placing his tubes close together; John Brayshay, 1856 (No. 1738); W. G. Ramsden, 1860 (No. 589); Babcock and Wilcox, and later boilers. In the case of the boilers of F. Maceroni, 1839 (No. 8229), W. E. Newton, 1849 (No. 12783), and A. W. Williamson and Loftus Perkins, 1859 (No. 2208), the movement of the steam and water was necessarily confused, in consequence of the method of connecting horizontal with vertical tubes which was adopted. In some other instances the horizontal, or horizontally inclined, tubes were closed or plugged at one end, and therefore only opened into boxes or headers at one, usually the front, end. This finds illustration in the boilers of Alban (about 1843), Kelly, Lane, Niclausse and Dürr, the four latter having either internal tubes or diaphragms for circulation of the water by separating the currents of steam and water. Both the "Barrow" boiler of J. and F. Howard and Root's boiler have a modification of the parallel coupling; whilst a recent one of F. E. Rainey has a combination of both series and parallel couplings in the same boiler, the series connections being of course short-circuited by this means.

A boiler constructed of horizontal tubes coupled in series and forming in this way a flattened spiral is not properly a coil boiler, because, not only is the horizontal tube the unit proper of the boiler, but also, in general, the bends or end connections are either not at all, or only slightly, exposed to the heat, and are not used as part of the heating surface for steam generation. The fact that there are joints to preserve at these parts is sufficient reason why they should be treated differently from the body of the tubes.

Similarly there is no reason why the boilers of Lane, Niclausse, Kelly, and Dürr should be considered as being anything but horizontal tube boilers, any more than should the boiler of Alban. The mere fact that they have provision for the circulation of the water in the horizontal tubes by means of internal concentric tubes, which Alban had not, only differentiates them as to completeness of detail and not as to the general form or design.

It is apparent that the action taking place in boilers of any of these groups is substantially the same as that which goes on in the others, in this respect, that the steam which is generated in any of the horizontal tubes must at once rise to the upper

surface of the tube along which it will proceed to the end. This is shown in the illustration of a glass model of such a boiler (Fig. 110). Where steam is being generated very rapidly a considerable proportion of the upper surface of the tubes will thus be in contact only with steam within, and although that portion may be shielded from the radiant heat of the fire, yet it is exposed to contact with flame and hot gases on the outside, and is therefore liable to be raised to a higher temperature than the lower half of the tube which retains water in contact with its surface. This tends to the production of strains in the individual tubes, which should be avoided. In the group with "series" connections this result is necessarily accentuated, as each tube in a series has to convey not only the steam generated within itself, but also all generated in the tubes immediately below it in that series. In result, too, this causes the topmost row or rows of tubes to be practically denuded of water; that which they contained at starting having been forced upwards into the steam-drum by the rush of steam from below, and the same cause operates in preventing any of that water draining back into these tubes from the steam drum. No water, or only a little in a frothy foam, can reach these tubes from below, so that in such cases there may be a row or two of tubes which are wholly raised to a higher temperature than those lower down, and this will introduce further strains in the structure of the boiler.

It is apparent that no advantage can be derived from causing the steam to be detained in contact with the water, but that, on the contrary, the steam once formed should be able to escape by a direct route straight to the steam chamber. For similar reasons, as soon as the steam and the water carried up by it have separated, the water should be returned by the most direct road to the point at which it is available for supply to the heating surfaces. Even with vertical water tubes a rapid generation of steam causes the projection of a good deal of water into the steam chamber along with the steam, and there is nothing in the horizontal tube design to cause that action to be less in its case.

Boilers of this design have the further disadvantage that, if placed athwartships in a steamer, they are liable to have their circulation of water and steam interrupted and even reversed

during and in consequence of the rolling of the ship in a seaway. As long, however, as the present rate of steam generation per square foot of surface continues to be the best result aimed at, it is probable that this design of boiler will be used, and will compare more or less favourably with other designs, worked under the same conditions.

Hancock's Boiler.—Amongst early examples of this form of boiler Mr. C. H. Wingfield advanced the one shown in Fig. 158, which he ascribed to Walter Hancock, who was best known in connection with the use of a cellular form of boiler in road vehicles. Mr. Wingfield said[1] that, "in connection with Hancock's boiler, it was not generally known that he at first used a boiler with horizontal tubes connected at their ends, Fig. 158. This he abandoned for his boiler of 1827, consisting of flat leaves," &c. Mr. Wingfield, however, did not mention from what source he derived his information, and the boiler illustrated was not patented by Hancock.

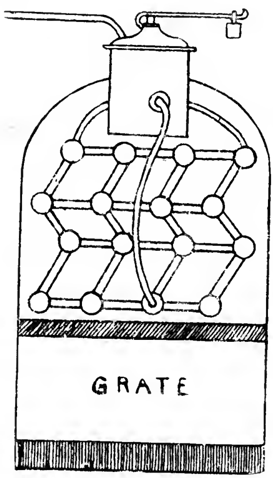


FIG. 158.

Griffith's Boiler. — Another early boiler made on this plan was the one employed by Mr. Griffith in his steam carriage[2] built by Bramah. This is shown in Fig. 159. Griffith's patent of 1821 described a boiler of horizontal tubes connected at the ends by semicircular bends, the feed water being caused to travel through the whole in series. In this instance of experimental work, however, he adopted the parallel system of coupling the tubes, as will be seen. We have it from Sir F. Bramwell[3] that this boiler never could be kept tight, so that the steam carriage did not succeed; and Mr. A. Gordon, in his "Historical and Practical Treatise upon Elemental Locomotion by means of Steam Carriages on Common Roads," records a similar result.

[1] Trans. Inst. Eng. and Shipbuilders in Scotland. Vol. xli., pp. 81-82.

[2] Gordon's Locomotion on Common Roads, p. 41.

[3] Reminiscences of Steam Locomotion on Common Roads. Section G. British Assoc., 1894. *Engineer* 17 Aug., 1894, p. 152.

Although only six horizontal tubes and two vertical boxes, or headers, are shown in the Fig. 159, similar rows of tubes and headers were placed behind these, so that there were 114 tubes in the boiler. Three transverse horizontal steam domes were placed above as shown. The horizontal tubes, Mr. Gordon remarks, "would not always contain water, and when empty, got so heated that no force pump could inject the water; on this account the invention was dropped."

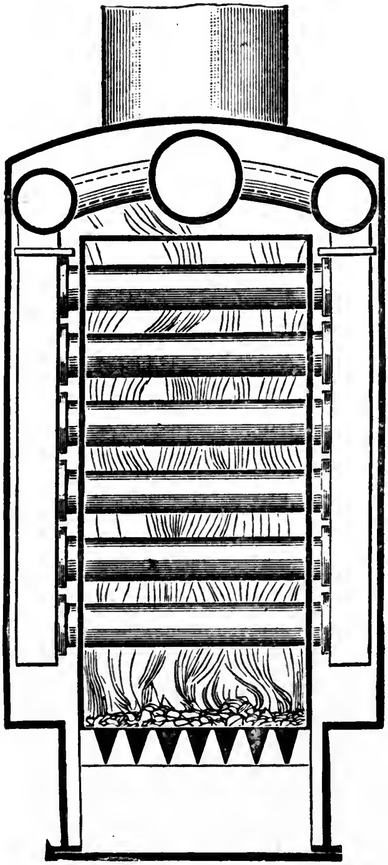


FIG. 159.

Andrew Smith's Boiler.—The boiler of Andrew Smith, mentioned above, possessed the original feature that, whilst the rows of horizontal tubes were connected in series, their diameter was increased as the rows ascended. This showed that he, at any rate, appreciated the effect of that mode of connection upon the steam and water circulation in the boiler.

Alban's Boiler. — About 1843 Dr. Ernst Alban, of Plau, Mecklenburg, introduced a water-tube boiler composed of horizontal tubes slightly inclined upwards towards the front end, at which they were screwed to the backplate of a rectangular chamber. Figs. 160, 161 and 162 illustrate this boiler. The tubes were of copper 4 inches in diameter, $\frac{1}{10}$th inch thick, and from $4\frac{1}{4}$ to $6\frac{1}{4}$ feet in length, according to the size of boiler wanted. The rows were disposed so as to break joint vertically, the

advantages of this arrangement in view of the circulation of the heated gases being apparent. (See on this point N. J. Suckling, "On Modern Systems of Generating Steam," Society of Engineers, 1874, and *The Engineer*, 28th February, 1873, and 29th May, 1874; and James Howden, "The Comparative Merits of Cylindrical and Water-tube Boilers for Ocean Steamships," Trans. Inst. N. A., 1894.) An English translation of Dr. Alban's treatise was published[1] in 1848, and his boiler was described by Mr. Vaughan Pendred in a paper on "Water-tube Boilers" (Transactions of the Society of Engineers, 6th May, 1867), and by Mr. D. K. Clark in "The Steam Engine," &c. (Vol. ii., p, 756). The back ends of the tubes were closed by a screw cover in each, which could be removed for the purpose of cleaning out the tube. The provision made for circulation of

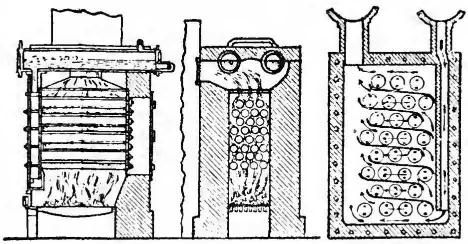


FIG. 160. FIG. 161. FIG. 162.

the water in the tubes was limited to certain arrangements in the front chamber. At the end of each tube there were two oval openings in the backplate of the chamber, the upper one for the escape of steam from the tube and the lower one for admission of water to the tube. The chamber itself was connected to two cylindrical horizontal vessels above, placed in the same direction as the tubes, and the connection from one of these was carried down to the bottom of the front chamber, whilst the other had access directly to the top of it. The intention of this was to convey the water from one down to the lowest point in the tube chamber, from which, in flowing upwards, it was directed across the rows of tubes by division plates, and these also served to direct the steam clear of the

[1] The High-Pressure Steam Engine, by Dr. Ernst Alban. Translated from the German by Dr. Wm. Pole, F.R.S. 1848.

tubes above, so that it collected on the side where it found the opening into the other horizontal vessel above.

Figures of proportions of this boiler and of results of working will be found in the papers quoted above.

Belleville's Boilers.—The first British patent taken out by Julien Francois Belleville was dated in November, 1852 (No. 725). It described a combination of horizontal and vertical coiled pipes, and, as made, the boiler was probably not unlike the one illustrated in Bertin and Robertson's "Marine Boilers" (p. 224) as having been tried in the "Biche," without success.

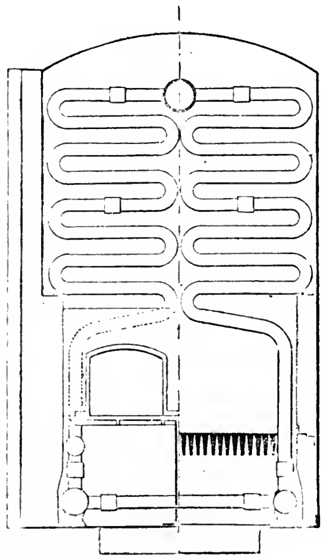


FIG. 163.

In July, 1856 (No. 1606), another arrangement of these coiled or serpentine tubes was proposed in which only horizontal tubes were employed. In both of these designs the water was first heated in the portions of the coils or tubes farthest from the fire, and after circulating in them was made to pass through those nearer the fire, finally finishing in those immediately over or at the side of the furnace. This was practically the flashing system, as the tubes exposed to the direct heat of the fire could never contain any water, although they might be useful in superheating the steam.

Further patents in 1860 (No. 155), 1865 (No. 3269), and 1866 (No. 2976), followed, from which the modern form of the Belleville boiler has been developed.

Patents were also taken out in 1869, 1872, 1880 (No. 5447), 1884 (No. 11851), 1889 (Nos. 14873 and 15356), and 1892 (Nos. 11615, 22250, and 22251), 1895 (Nos. 1336 and 1729), 1896 (No. 14868). An early form of the Belleville boiler, in which junction boxes were used only at the front, the tubes being bent at the back so as to bring both ends parallel to the front, one being above the other, is illustrated in Mr. Thornycroft's paper on

Water-tube Steam Boilers in Min. Proc. Inst. C. E., Vol. xcix., Plate I., Figs. 3a.

The first of these latter patents (1860) describes the boiler illustrated in Fig. 163, which is quite a coil boiler, but did not succeed when tried in the "Argus" and the "Sainte Barbe" in 1861. This form bears some resemblance to the earlier arrangement of parts in the Du Temple boiler.

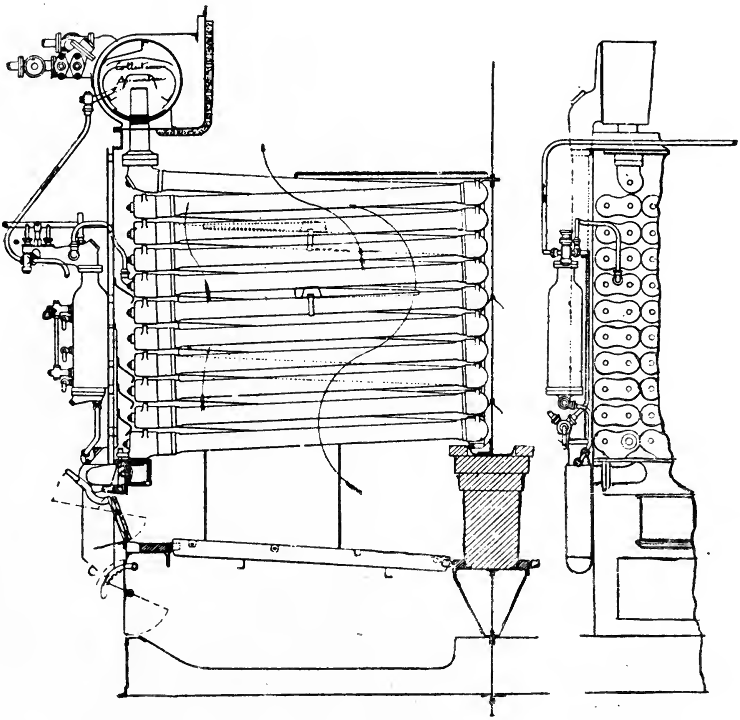


FIG. 164.

In the boilers of 1866, 1869, and 1872, the feed inlet enters directly opposite the end of the lowest horizontal tube in the front box or header, and the steam separator is merely a tube of small diameter surmounting a similar tube used as a collector, small branch pipes connecting the two. In the later boilers the connecting boxes at the ends are placed horizontally, instead of vertically as formerly, a feed collector and arrangements for

Front elevation

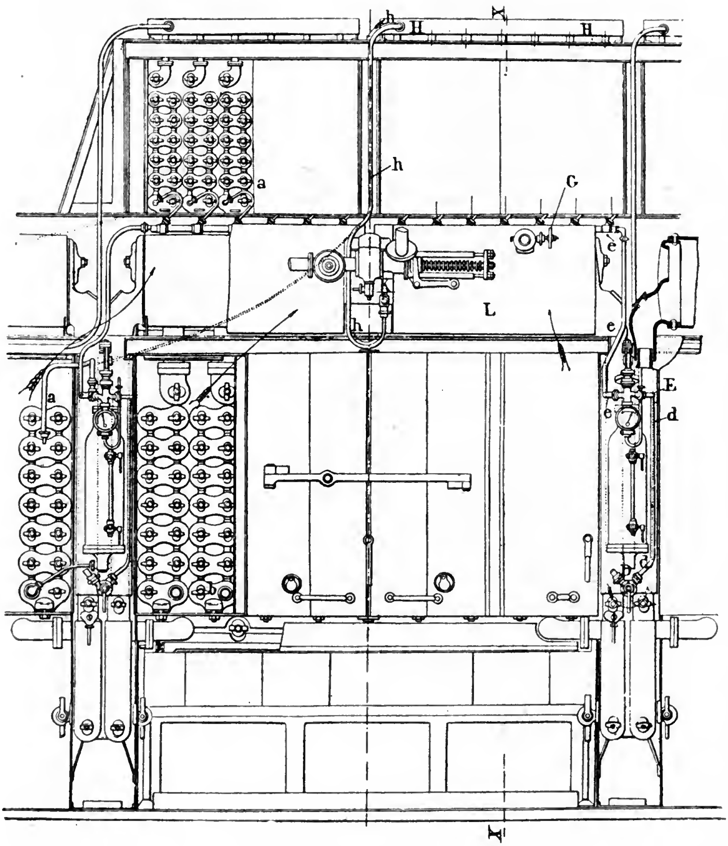


FIG. 165.

Side elevation.

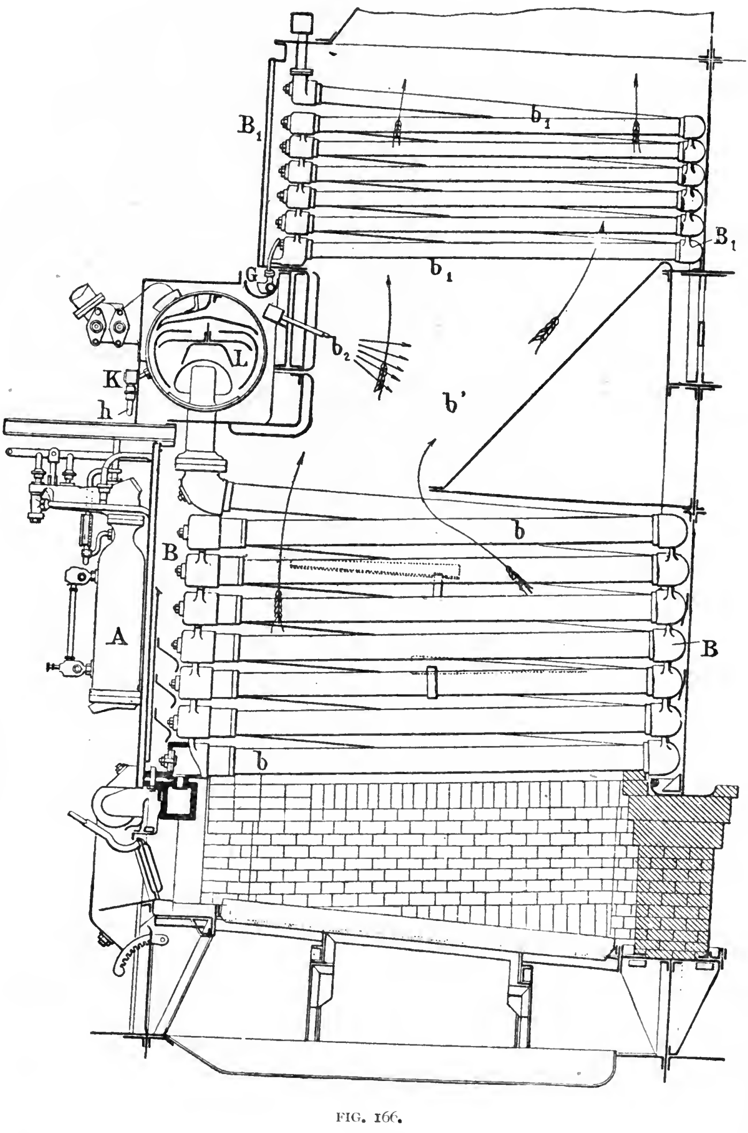


FIG. 166.

automatic regulation of the feed are added, and the steam separator is a vessel of cylindrical form with internal baffle plates. The latest forms have in addition a feed-heater composed of short tubes, arranged like the steam generating tubes, placed in the flue space above the generator.

Fig. 164 shows the modern form without feed-heater, and Figs. 165 and 166 the arrangement finally adopted with feed-heater. Detailed descriptions will be found in Bertin and Robertson's "Marine Boilers," Sennett and Oram's "Steam Engine," and in various papers in the Proc. Inst. C. E. and Trans. Inst. N. A.

The Belleville boilers of H.M.S. "Diadem" are illustrated in *The Mechanical Engineer* of 9th April, 1898.

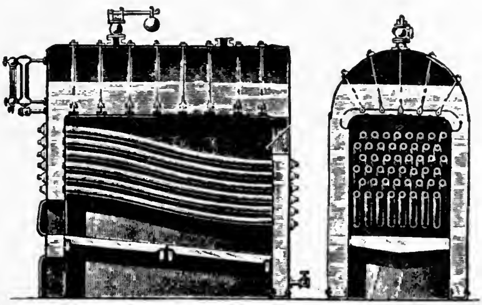


FIG. 167.

Wilcox's Boiler.—The boiler shown in the accompanying illustration (Fig. 167) is said by Professor Thurston to have been invented by Stephen Wilcox in America in 1856, and thus in a certain way to have led up to the Babcock and Wilcox boiler of to-day, although there were some intermediate steps.

Benson's Boiler.—A very interesting water-tube boiler in this class of horizontal or horizontally inclined tube boilers was patented by Martin Benson in 1858 (No. 1903), and again in 1861 (No. 834). The small horizontal tubes of 1 inch or 1½ inch diameter were connected by semicircular cast iron bends or junction pieces at the ends, and were arranged in series in a vertical direction to form a number of flattened spirals placed side by side. The bends were placed vertically at the back of the boiler and horizontally at the front end of the tubes, so that

one vertical section or compartment of the boiler consisted o two horizontal tubes side by side but in rows zig-zagged or "staggered" in an upward direction (see Figs. 168 and 169. In describing this boiler to the Institute of Mechanical Engineers (Proceedings 1859, p. 264[1]), Mr. J. F. Spencer said that the uncertainty of what may be termed natural circulation had led

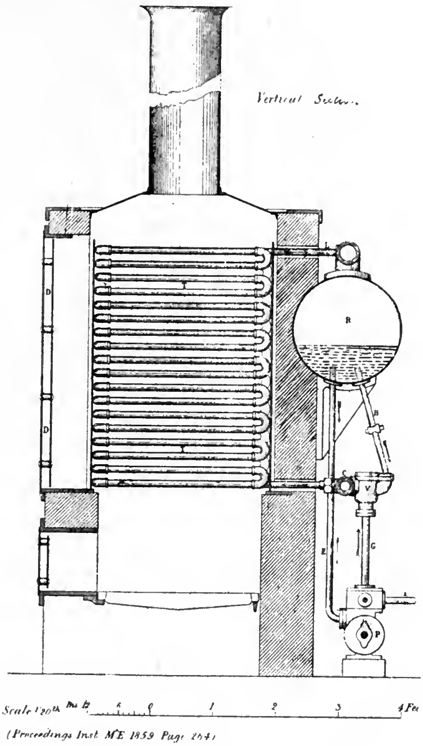


FIG. 168.

to the introduction of mechanical circulation as a distinctive feature of this boiler, and that ten to twenty times the quantity of water required for steam might be passed through the boiler in a given time.

The pump for mechanical circulation was connected with the

[1] See also Proc. 1861, p. 30, and Plate xxiii.

steam receiver, which also acted as a separator and water chamber, and showed the water level of the boiler, being placed at the back or side of the boiler and not above the tubes. "It will be evident," said Mr. Spencer, "that a small amount of power is required to work the circulating pump, since

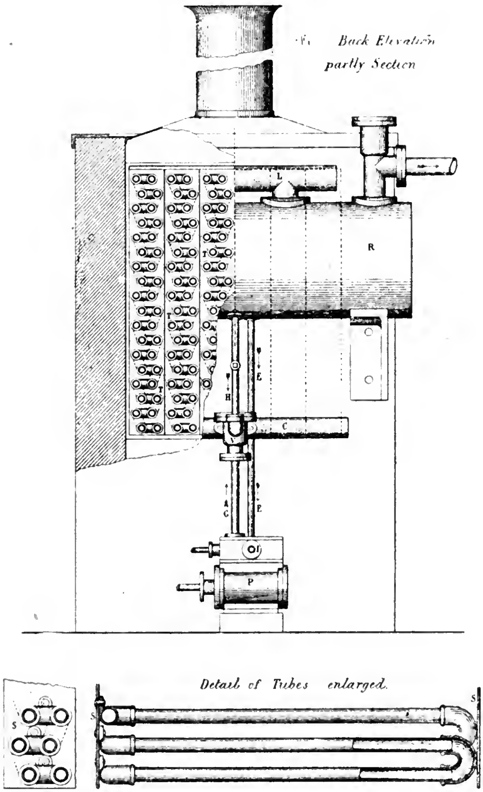


FIG. 169.

the pressure is almost equal on each side of the piston, so that, whether this pressure be 100 or 500 lbs. per square inch, only the friction of the water has to be overcome in effecting the circulation. A boiler of 100 nominal horse-power would require a circulating pump of only 7 inches diameter and 12 inches stroke, making 50 revolutions per minute." Supposing

that 10 cubic feet of water were evaporated per hour, about 100 cubic feet would be passed through the circulating pipe and the tubes by the circulating pump. In addition to the circulating pump, an ordinary feed pump was used to supply the deficiency of water caused by evaporation.

Williamson and Perkins Boiler.—In September, 1859 (No. 2208), A. W. Williamson and Loftus Perkins patented the boiler composed of horizontal water tubes united by short vertical tubes, which was afterwards known as Perkins' boiler. This boiler was described and illustrated in the Proceedings of the

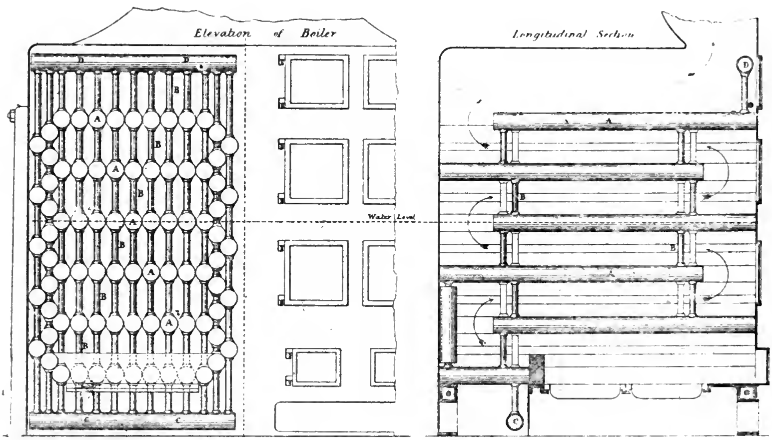


FIG. 170.

Institute of Mechanical Engineers in 1861 (page 95 and Plate xxiii.), Fig. 170, and a later form was described by Mr. Loftus Perkins in 1877.[1] (See also Perkins and Harris, 1880, No. 168.) Fig. 171, 172 and 173 shows the later form as arranged for a marine boiler. The joints connecting the horizontal tubes with the short vertical tubes were all screwed, but there was no proper provision made in this boiler for the circulation of the water. In fact, Mr. Perkins used to claim as a feature of the boiler that it made steam by "foaming" and not by means of circulation as properly understood. Some of the fallacies

[1] Proc. Inst. Mech. Eng., 1877, p. 117.

grouped around this system were exposed in an article (by the author of this work) which appeared in *Engineering* of 30th March, 1877 (Vol. 23, p. 251) entitled "Amateur Science at the Royal United Service Institution." Examples of Perkins' boilers were fitted in the s.s. "Anthracite" and in the s. yacht

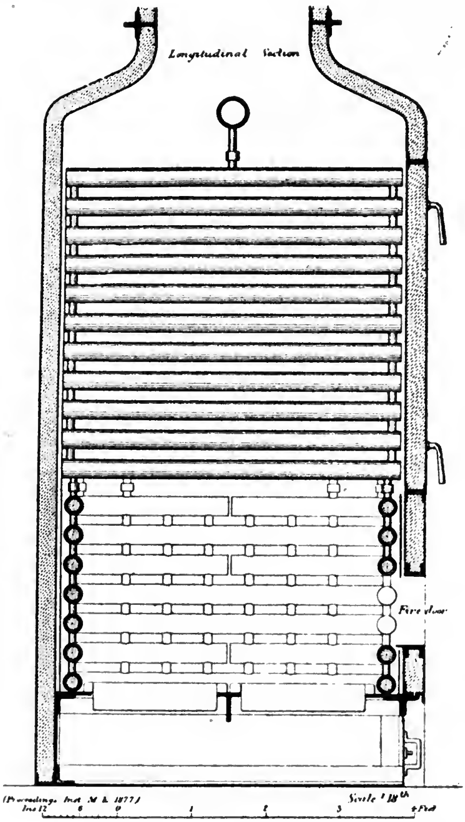


FIG. 171.

"Wanderer," but these were not permanently successful. Little, however, was allowed to become known of their history after preliminary trials.

Boilers of the s.s. "Montana" and "Dakota."—There is a strong family resemblance between the Perkins boiler and the

boilers fitted in 1875 by Messrs. Palmer, of Jarrow-on-Tyne, in the steamships "Montana" and "Dakota." In the latter the diameters of horizontal tubes and of the vertical connecting tubes or necks are larger, so that apparently there is more freedom of circulation possible, but this was neutralised by

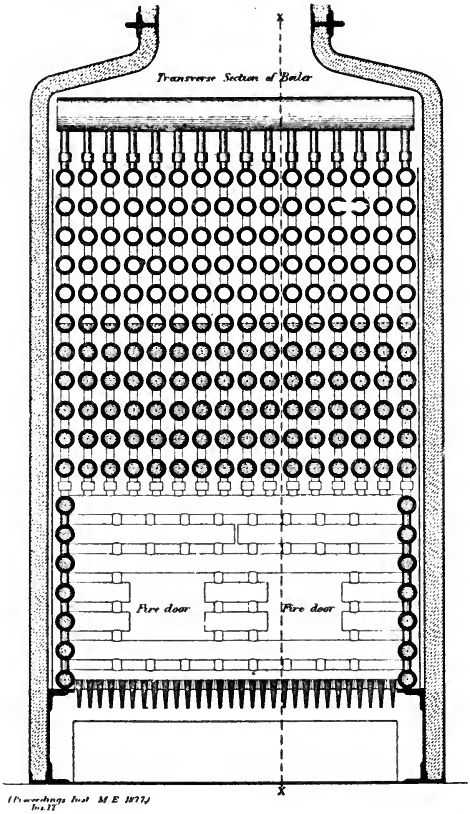


FIG. 172.

inadequate steam and feed connections. Moreover, the vertical necks had to serve for both the ascent of the steam and any water carried up by it, and the descent of the water so carried up. Figs. 174 and 175 show the profile of these boilers, particulars of the trials of which were given by Mr. W. Parker (in

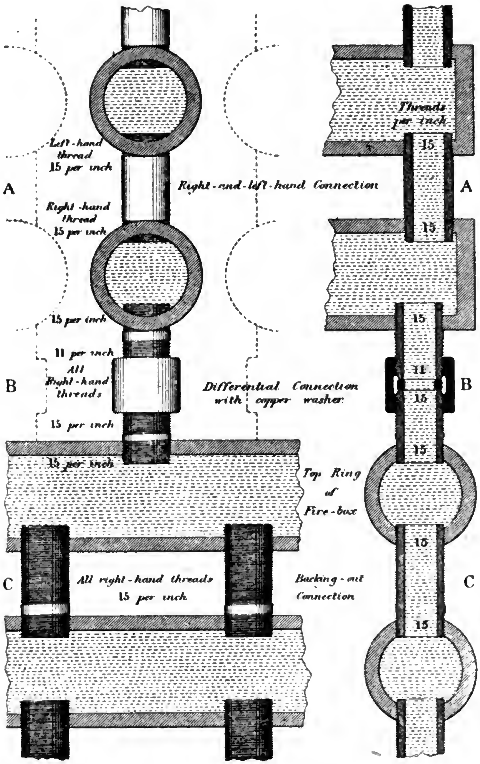


FIG. 173.

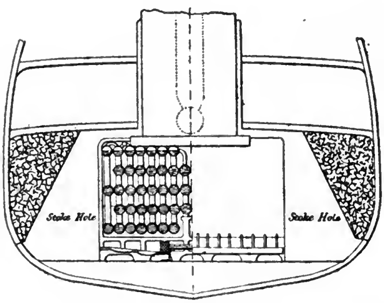


FIG. 174.

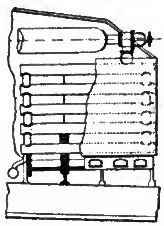


FIG. 175.

Min. Proc. Inst. C. E., Vol. xcix., p. 106) and by Mr. J. Fortescue Flannery in Trans. I.N.A., 1876.

Ramsden's Boiler.—In the boiler patented by Mr. W. G. Ramsden in 1860 (No. 589) horizontal tubes of comparatively large diameter were connected at their ends to vertical chambers,

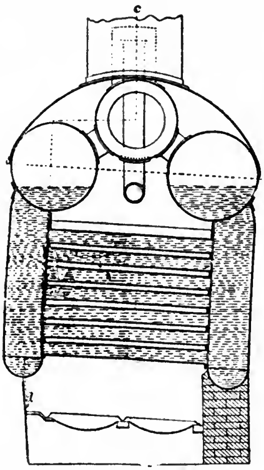


FIG. 176.

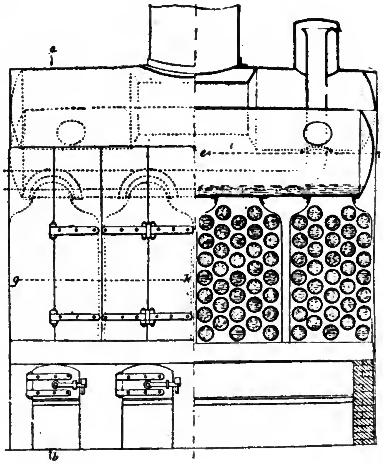


FIG. 177.

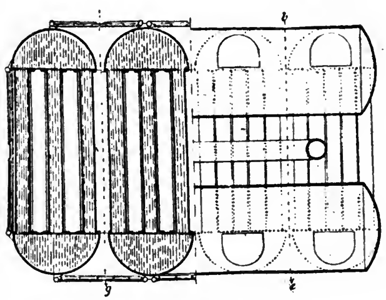


FIG. 178.

semi-circular in cross-section. This boiler is represented in Figs. 176, 177 and 178, which show the boilers fitted in the steamships "Amalia" and "Palm." Having been worked with sea-water, these boilers were practically destroyed by incrustation after about four years' work.

Babcock and Wilcox Boilers.—The original Babcock and Wilcox boiler was constructed of cast iron, and is illustrated in Professor Thurston's "Manual of Steam Boilers," from which Fig. 179 has been taken. It was introduced in America, and was subjected to various improvements in design, in which the cast iron headers and tubes were replaced with wrought iron. British patents were taken out in 1880 (No. 2615), 1881 (No. 5289), 1884 (No. 13041), 1885 (Nos. 1836, 3979, 4133, 4134, 10821), 1886 (No. 5887), 1887 (Nos. 3059, 8228, 11789, 11887), and in 1890, 1891, &c.

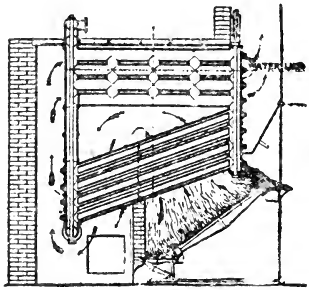


FIG. 179.

The Babcock-Wilcox marine boiler is shown in a patent taken out in 1896 (No. 24617).

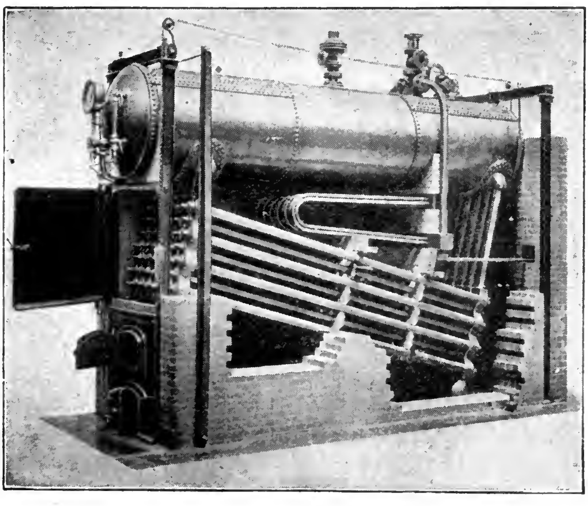


FIG. 180.

Various details were also patented by C. A. Knight and others connected with the boiler. After considerable success in land installations, it was introduced in vessels of the American navy, and a modified form for marine use was fitted in the s.s. "Nero"

and some other merchant vessels, and in H.M.S. "Sheldrake," in this country. The land form is also in extensive use in this country.

In the land boiler the horizontally inclined tubes incline downwards from front to back, and are secured at each end to wrought steel headers of square section and sinuous form vertically, so that the tubes are "staggered" to baffle the gases in their movement amongst them. A cylindrical steam and water

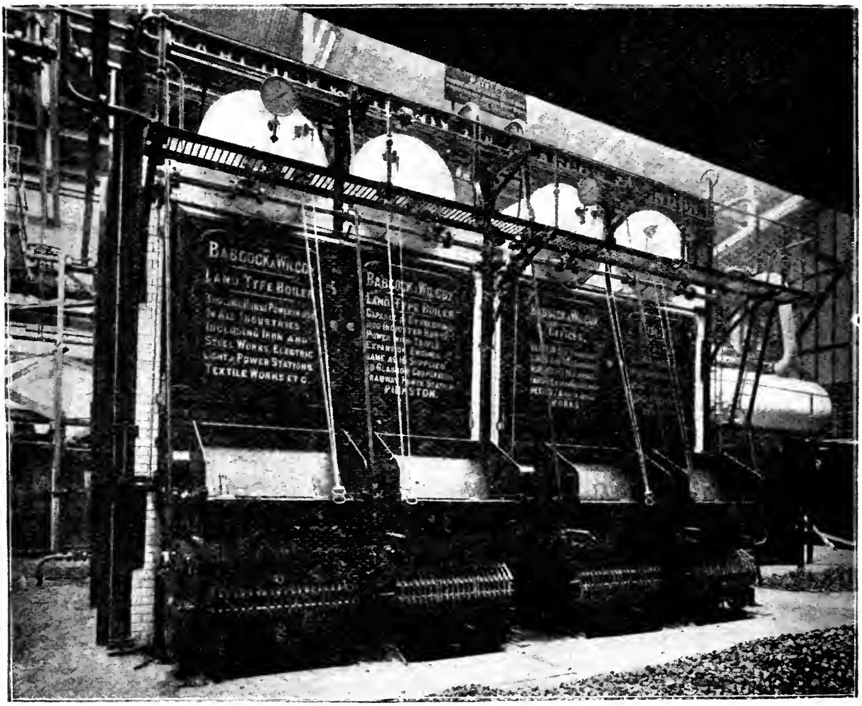


FIG. 181.

drum runs longitudinally from front to back above the tubes, and the headers are each separately connected to it at either end by vertical tubes or nipples. A mud collector is connected to the lower side of the back headers. The working water level being at about the middle of the steam and water drum, the movement of the water in circulation is always in the same direction, upwards through the inclined generating tubes and

the front headers and downwards through the back headers. Figs. 180, 181 and 182 show this form and some details.

In the marine form each of the inclined tubes is replaced by a group of four tubes of small diameter, and there are two

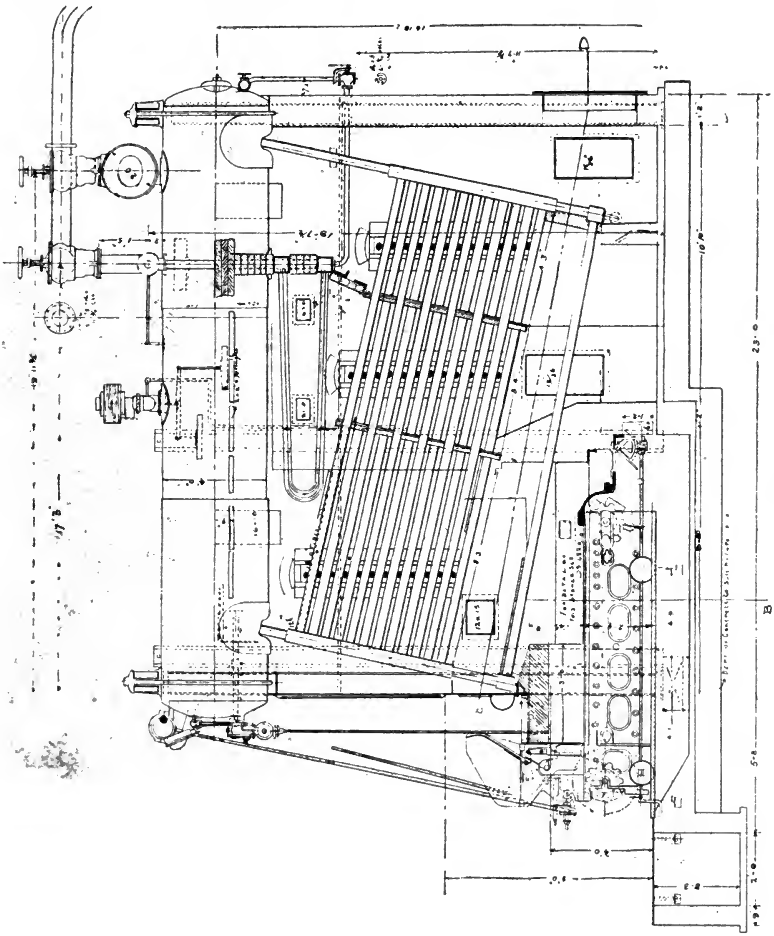


FIG. 182.

drums above—the larger one placed across the boiler at the top of the back headers, which are connected to it by short direct nozzles. In this drum the water level is at the centre, as in the land boiler drum, but there is a smaller drum a little above it,

and alongside, which is used as a feed purifying chamber, the feed being introduced into it. In the boiler of the s.s. "Nero" the upper chamber was used as a steam-chest, and there were

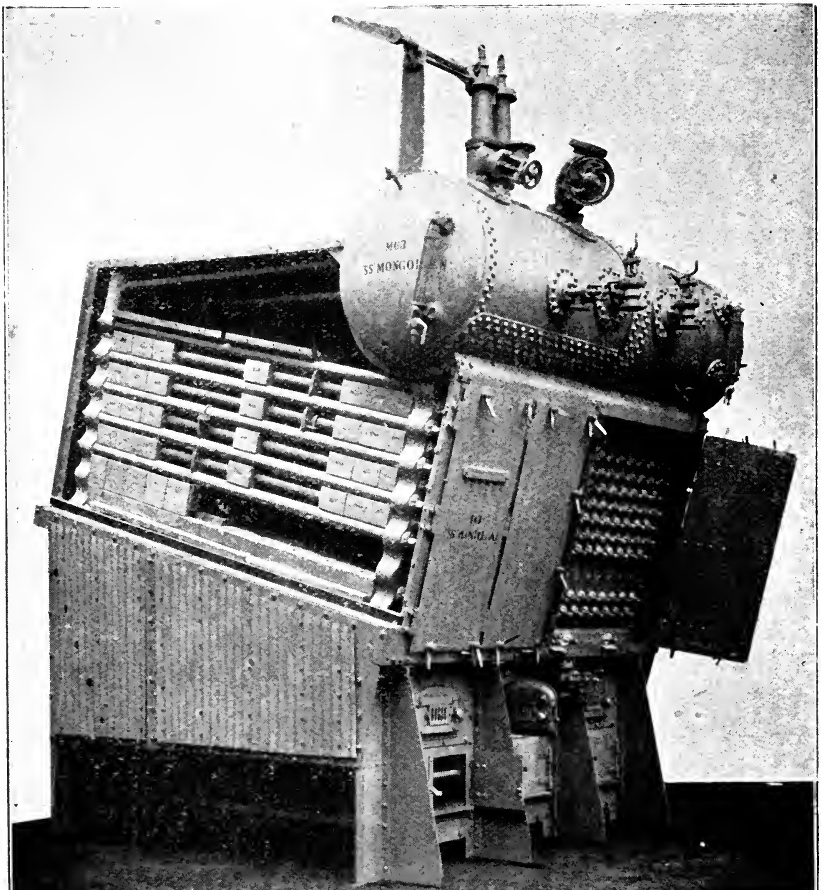


FIG. 183.

vertical water tubes set round the boiler to form a casing, but these seem to have been removed in the later examples. The front headers are connected to the steam and water drum by tubes passing horizontally across the top of the inclined tubes.

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Special fittings with metal to metal joints are made for the hand holes, and so arranged that, should a holding bolt break, they are held in place by the steam pressure.

Figs. 183 and 184 show the later arrangement of this boiler. An illustration of the "Nero's" boiler in outline will be found in the *Engineer* of 21st July, 1893, page 73, Fig. 1.

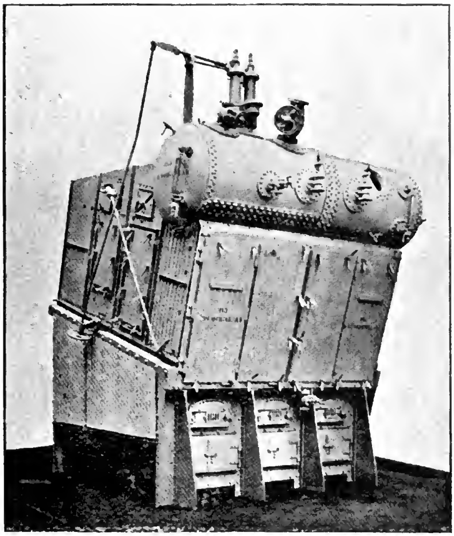


FIG. 184.

Root Boiler.—The Root boiler was introduced in America shortly after the Babcock and Wilcox boiler, but preceded it in this country, having been patented in 1870 (No. 1675), and, after some use in land installations, having been tried in the steamer "Birkenhead" in 1872.[1] The horizontally inclined tubes, usually about $4\frac{1}{2}$ inches diameter, are sloped downwards towards the back, and are screwed at back and front into rectangular box castings, which are connected vertically by hollow castings bolted on and forming means of communication from tube to

[1] See *Engineering*, 21st April, 1876.

tube. These hollow castings are so placed as to give a zig-zag course of ascent for the steam and water. Figs. 185 and 186 show the arrangement finally adopted as the most satisfactory. A later arrangement, introduced by Messrs. Conrad Knap and Co., having bent pipe connections between the various box castings instead of the American bracket-shaped hollow castings aforesaid, is shown in Figs. 187, 188 and 189. A description of the boilers fitted in the "Birkenhead" and "Malta" was given by Mr. J. Fortescue Flannery in a paper "On Water-tube Boilers" in Trans. Inst. N.A., 1876 (Vol. xvii., p. 259).

This boiler, as well as the one next to be referred to, has a modified arrangement of the coupling "in parallel," inasmuch as there are not headers common to all the tubes at either end of these, but a number of small passages formed by box castings or the like, by means of which the steam and water are passed from tube to tube, or zig-zagged upwards.

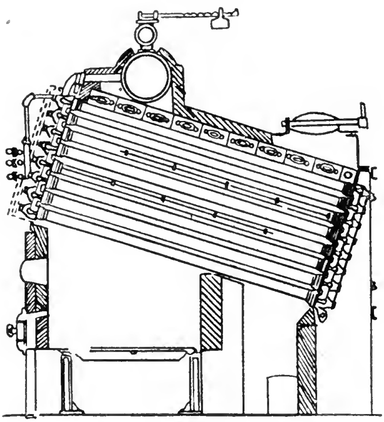


FIG. 185.

Howard's "Barrow" Boiler.—The horizontal tube boiler introduced by Messrs. J. and F. Howard in 1866, which was afterwards called the "Barrow sectional boiler," was described in one form by Mr. David Joy to the Iron and Steel Institute in 1875 (see Vol. No. i., 1875, p. 220, and Plates). A later form is shown in Fig. 190, taken from D. K. Clark's "Steam Engine." The tubes were inclined upwards to the back of the boiler, where five of the six tubes forming one vertical group were coupled to a vertical collecting pipe. At the front the feed-water was introduced into the lowermost tubes from a square cast iron chamber laid horizontally across the front of the boiler, and the tubes above this to the fifth row were closed by cast iron neck pieces screwed into the ends with cast iron covers bolted on. The fifth and sixth rows had a passage from one to the other provided in front, these two rows being above the

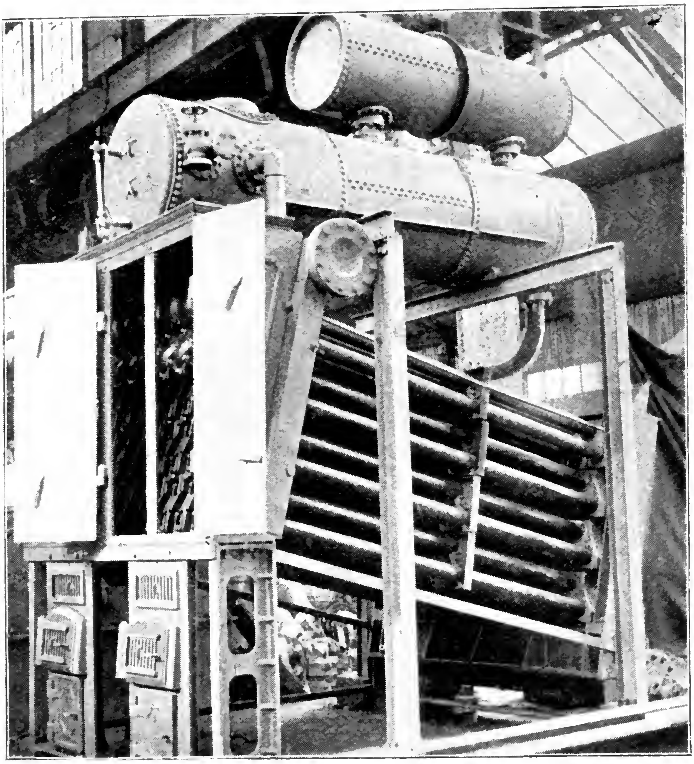
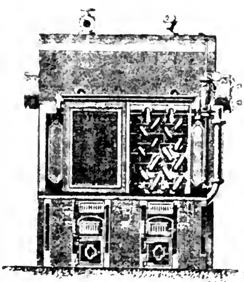
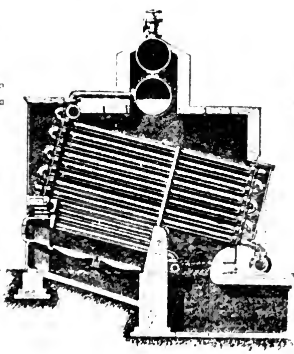


FIG. 186.





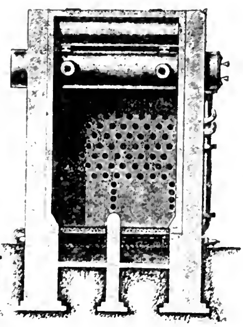


FIG. 187. FIG. 188. FIG. 189.

water line, so that the steam should pass from the collecting pipe through these tubes consecutively to the steam drum. The connections between the tubes are not so complete in this case as in Root's boiler, and promise difficulty in circulation of the water. The form shown in 1875 was preferable in this respect. The Howard boiler arranged for marine use was illustrated in Mr. J. Fortescue Flannery's paper "On the Construction of High-Pressure Steam Boilers" (Min. Proc. Inst. C.E., Vol. liv., p. 123).

It was introduced into the steamers "Fairy Dell," "Meredith," and "Marc Antony" about the year 1870, but was not

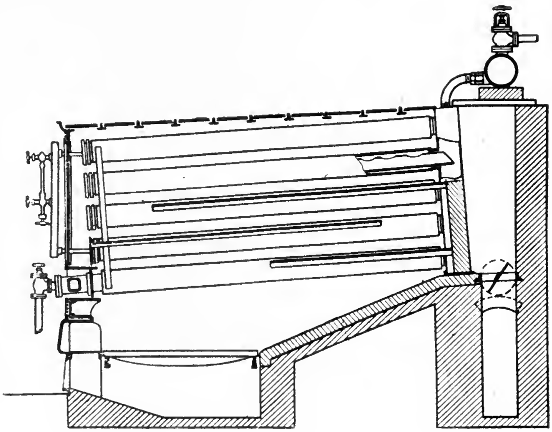


FIG. 190.

very successful. Particulars of the boilers of the "Fairy Dell" and "Marc Antony" were given in *Engineering* of 3rd March 1871 (Vol. xi., p. 155), and by the late Mr. W. Parker in Min. Proc. Inst. C.E., Vol. xcix., p. 106.

Watt's Boiler.—A marine boiler of the horizontally inclined water tube design was patented by Mr. John Watt in 1871 (No. 3011; see also No. 14430, 1890), and brought forward by him in a paper "On Water-tube Boilers" read to the Liverpool Polytechnic Society in 1874 (see *Engineering*, 27th March, 1874, pp. 234-236). It was also described in Mr. Flannery's paper above quoted. Figs. 191 and 192 illustrate this boiler.

The horizontally inclined tubes were connected at each end

to a flat rectangular chamber embracing the whole of the tubes in one boiler. This chamber was stayed to give it the necessary strength, the stay bolts also serving as studs for fastening on the covers placed opposite the ends of the tubes on the outside of both chambers.

Suckling's Boilers.—Some interesting features were embraced in the boiler designed by Mr. N. J. Suckling and illustrated in the *Engineer* of 28th February, 1873.

Suckling's British patents are—1872 (Nos. 2747 and 3893), and 1875 (No. 3494).[1]

In his paper "On Modern Systems of Generating Steam," read to the Society of Engineers, London, on 4th May, 1874 (see the *Engineer*, 29th May, 1874, and Transactions of the

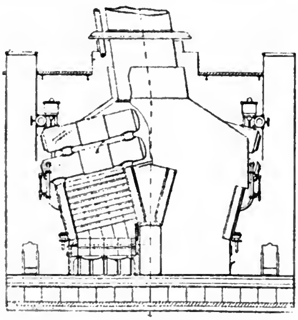


FIG. 191.

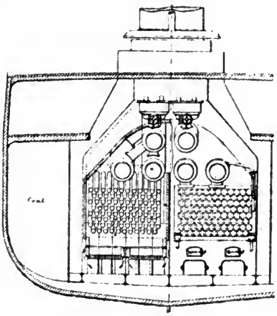


FIG. 192.

Society of Engineers), Mr. Suckling set forth many of the requirements of a good boiler; but it almost seemed as if, in order to secure some of these, he had been compelled to sacrifice others which are quite as necessary. Mr. Suckling's boiler, shown in Figs. 193, 194 and 195, was composed of horizontally inclined generating tubes arranged over the furnace so as to "break joint" or cause the gases to take a zig-zag course in moving upwards. The front ends of the tubes had heavy wrought iron flanges screwed on, and the back ends had wrought iron rings welded in, to which were secured wrought iron covers bolted on and having each a screwed pipe connection at the centre. Small straight or curved pipes led from these to large external tubes which acted as downcomers for the water and separators of steam and water. Every generating tube drew its own

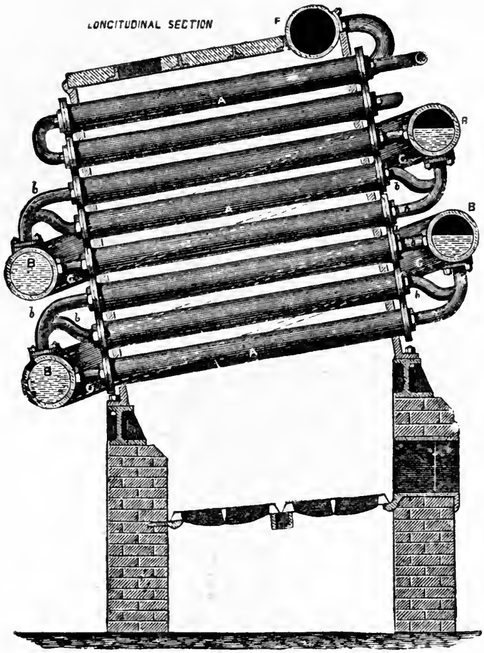


FIG. 193.

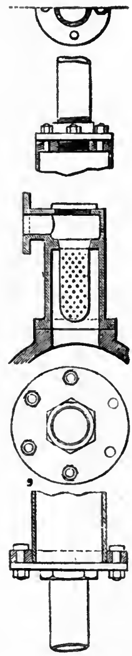


FIG. 194.

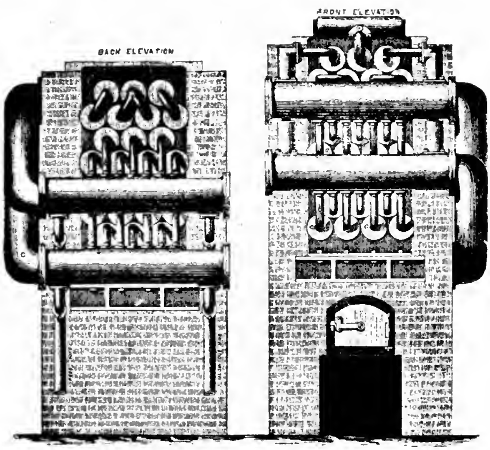


FIG. 195.

supply of water from the downcomer, and all the joints were outside the boiler, but the loss of heat by radiation from so large an area of outside connections must have been considerable.

Hardingham's Boiler.—Patents for concentric tube boilers of the horizontally inclined type were taken out in 1882 by R. H. Brandon (for C. Gamper) on 12th April (No. 1745), and by G. G. M. Hardingham on 18th October (No. 4956). The former one does not seem to have been brought out, but Mr. Hardingham's boiler has been described in *Engineering* of 11th

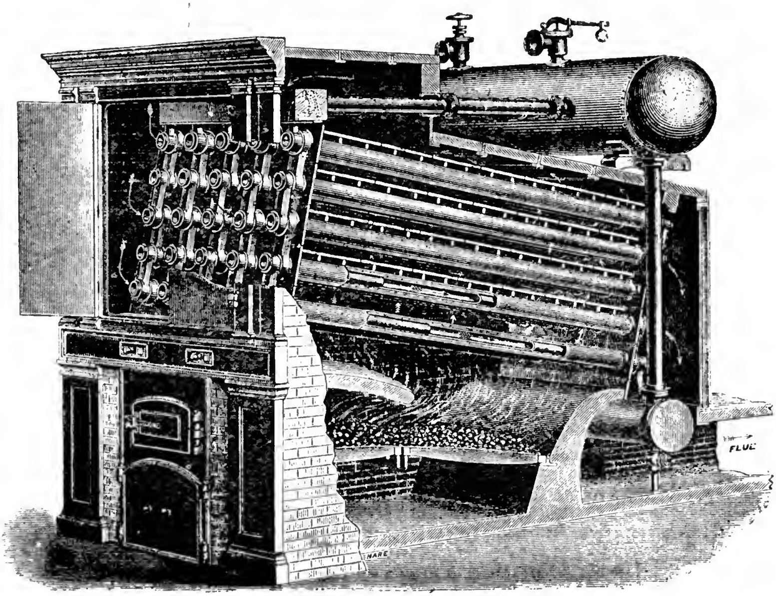


FIG. 196.

January, 1884, and put on the market. Improvements were patented in January, 1884 (No. 565). The water tube, which is the outer tube, is screwed or fastened otherwise to the socket plate of a cast iron box and the inner or fire tube is packed by a screw gland to the outer face of the same box. The boxes are arranged so as to leave a passage for the steam and water up to the steam drum. See Fig. 196.

The course of the hot gases is as shown—first, directly upwards over the outsides of the water tubes and then to the

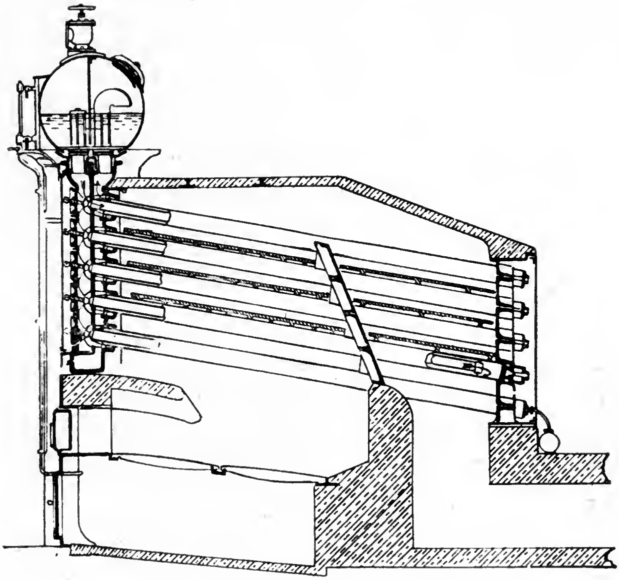


FIG. 197.

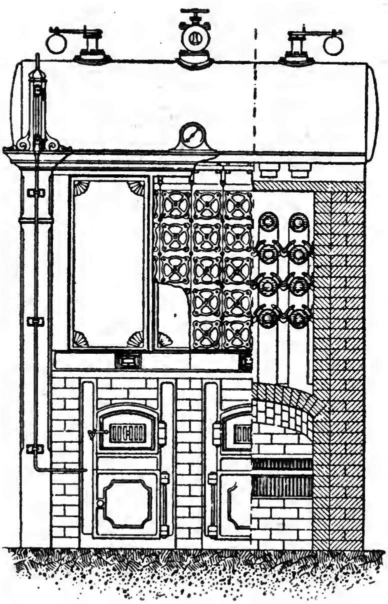


FIG. 198.

front or elevated end of the boiler, and downwards through all the inner tubes to a flue at the back. Provision is made for water circulation and the boiler is well proportioned.

Lane's Boiler. — Mr. H. Lane took out a patent in January, 1883 (No. 209), for a horizontally inclined tube boiler with box headers, very like those of the Root boiler, but he followed in May, 1883 (No. 2405), and later (No. 4033) with patents for the boiler shown in the Figs. 197 and 198. In this design the horizontally inclined tubes are closed by

a screwed plug at their lower ends and have each an internal circulating tube for water. At the front is an upright square chamber having a vertical partition, dividing it into the compartments internally. The inner circulating tubes are fastened into this partition and the outer tubes to the back of the chamber. A steam drum is placed on the top of the chamber, and the

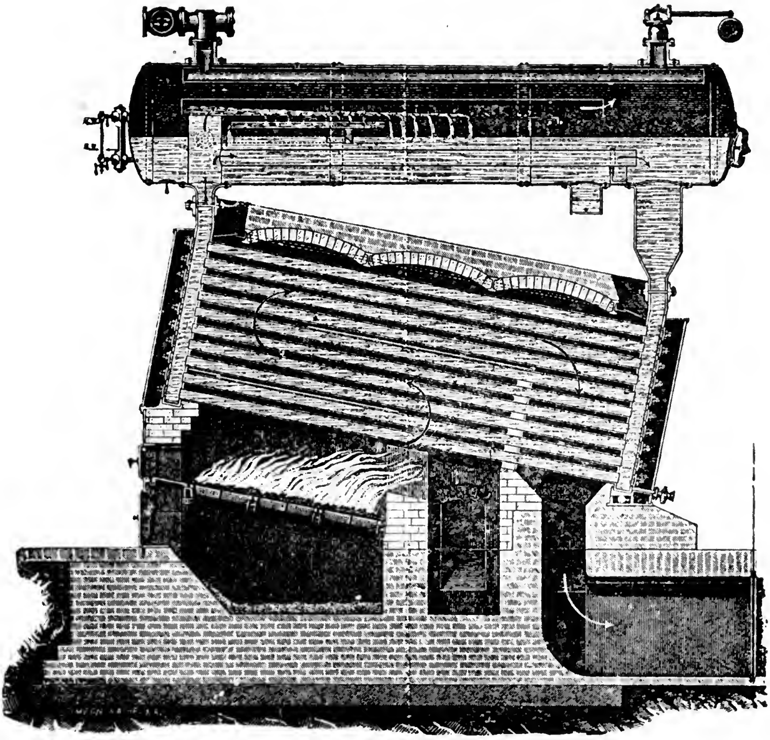


FIG. 199.

upward current of steam and downward current of water do not interfere with one another. Dimensions and details are given in a description in Vol. ii. of D. K. Clark's "Steam Engine," pp. 773-777.

Steinmüller Boiler.—The boiler brought out in Germany by Messrs. L. and C. Steinmüller, of Gummersbach (Rhine Province), was patented in this country in 1876 (No. 3646). 1884

(No. 11105), 1889 (No. 5868), and 1890 (No. 1348). It is to some extent like Watt's boiler, having flat stayed chambers at

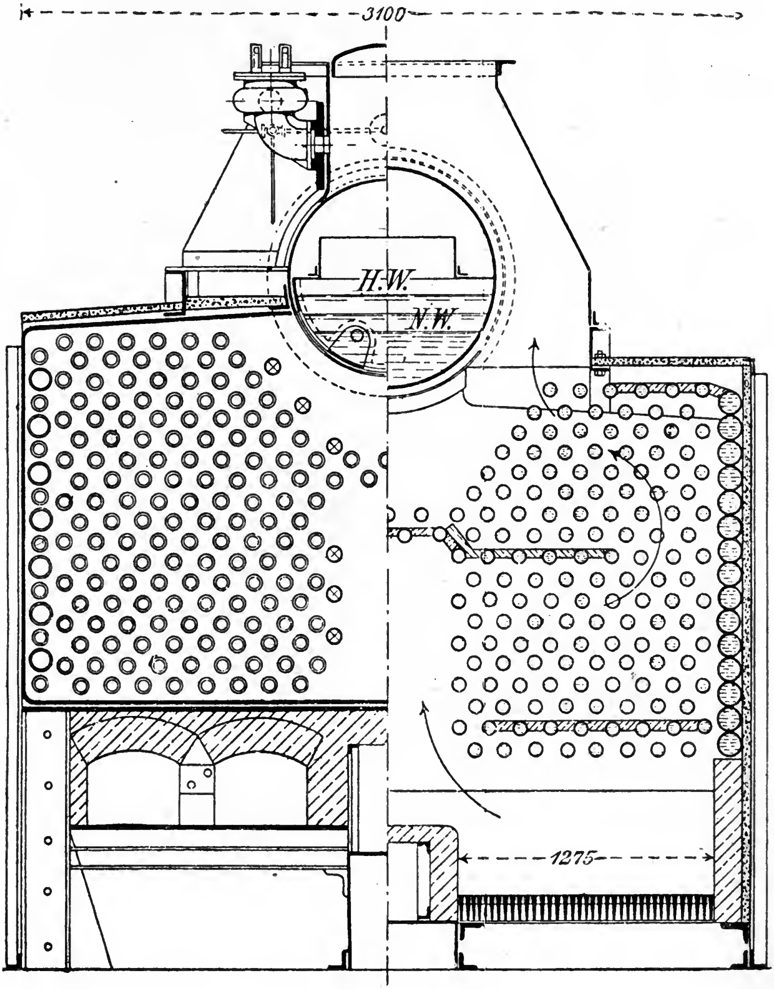


FIG. 200.

each end of the horizontally inclined tubes. The steam dome is, however, placed horizontally (not inclined, as in Watt's boiler) in the centre between two boilers, and the generating tubes are

grouped around it on its under side. Figs. 199, 200, 201, and 202 show this boiler.

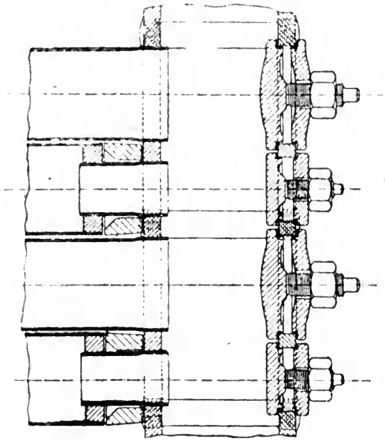


FIG. 201.

For marine use the outside vertical row of tubes is arranged so that the tubes touch, a small neck piece connecting alternate tubes with the flat chamber wall so as to have sufficient metal between the openings for strength.

The Büttner Boiler. — Another boiler of this class in use in Germany is the Büttner boiler, patented in this country in 1873 (No. 412), and by H. Simon (for F. L. A. Büttner) in 1879 (No. 566), and 1891 (No. 10237). It has the horizontally inclined tubes fastened into flat chambers at each end like the Watt, Steinmüller, Heine, and other boilers. There is, however, a row of shorter tubes immediately over the fire connected to a common transverse tube at their lower ends, this transverse water tube being connected to a similar tube at the foot of the back header.

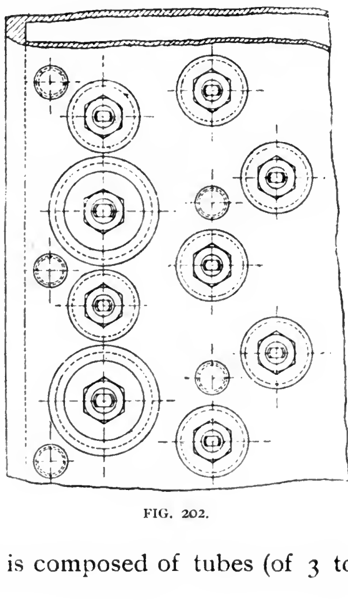


FIG. 202.

The Niclausse Boiler.—The Niclausse boiler was, according to M. Bertin ("Marine Boilers," p. 268), developed from the Collet boiler, so that its introduction dates from the publication of the Collet design, although it has been greatly altered in details. As now known, the Niclausse boiler is composed of tubes (of 3 to

4 inches diameter) slightly inclined from the horizontal, with headers at only one end, the other end of the tubes being left free, so that there is no rigidity to resist expansion lengthwise. The free end of each tube is closed by a screwed cap, and the

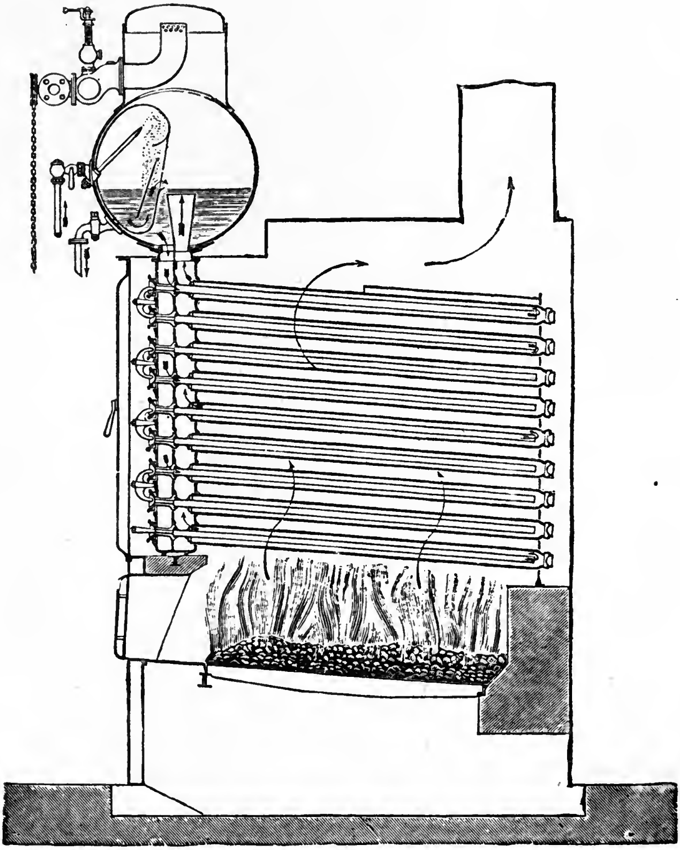


FIG. 203.

front end is secured by two coned joints to both outer and inner walls of the header, although it communicates only with the inner of the two chambers or passages into which the header is divided by a partition. The outer chamber is in communication with the smaller tubes, of which one is inserted concentrically

for circulation of water, in each of the larger generating tubes. At the top of the header is the steam drum, and as the water level stands at about the centre of this cylinder, circulation of the water commences as soon as heat is applied to the tubes.

The water flows down the outer or downcast half of the header, through the small inner tubes, which project nearly the full length of the generating tubes, and back by the outer

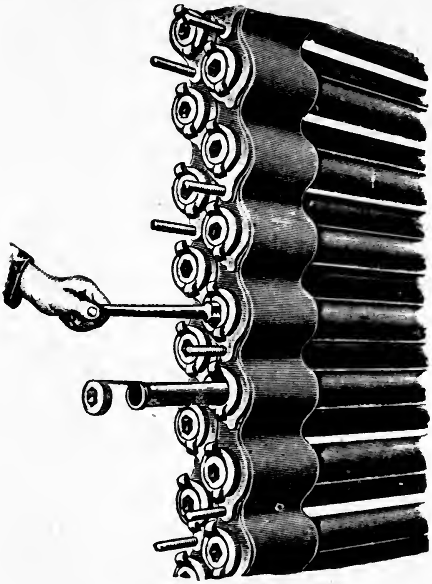


FIG. 204.

FIG. 205.

tubes, the steam and foam escaping by the upcast half of the header. The constructional details have been arranged with great ingenuity in order to simplify both erection, examination, and repair of the boiler. The method of attaching the tubes to the header by means of coned joints and "lanternes" (which the sleeves forming continuations of the tubes are called) is a salient feature of this boiler, and this improvement over the original Collet design is due to the Messrs.

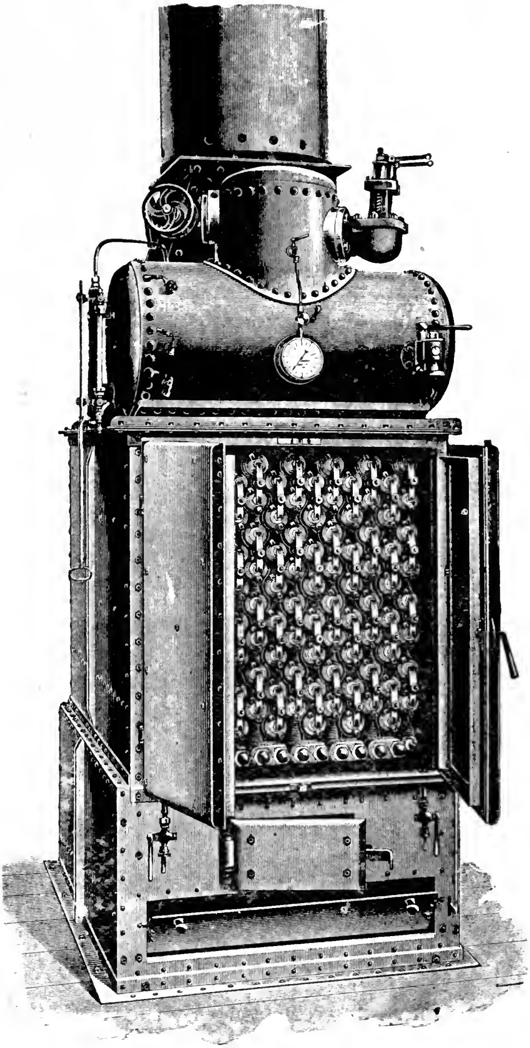


FIG. 206.

Niclausse. It has been fully described by Mr. Mark Robinson,[1] Mr. J. T. Milton,[2] and M. Bertin,[3] and is fairly represented in

[1] Trans. Inst. N.A., 1896, Vol. 37, p. 119. Also British Assoc., 1899.
[2] Trans. Inst. N.A., 1894, Vol. 35.
[3] Marine Boilers, pp. 271, 272.

section by Figs. 203, 204, and 205, whilst the boiler as a whole is shown in Fig. 206.

Illustrations of the "Niclausse" boiler will also be found in *Engineering*, Vol. lx., page 91, and of the Niclausse small tube boiler, in the *Electrical Engineer* of 13th October, 1899, page 461.

Records of tests will be found in Chapter IX., and in the papers quoted above, and some interesting points of comparison between this and other boilers will be met with in Mr. Mark Robinson's paper read at the 1899 meeting of the British Association. The first British patent due to M. Collet is dated 15th February, 1878 (No. 644), but the subsequent patents referring to the Niclausse boiler are 1891 (No. 1052), 1893 (Nos. 10136

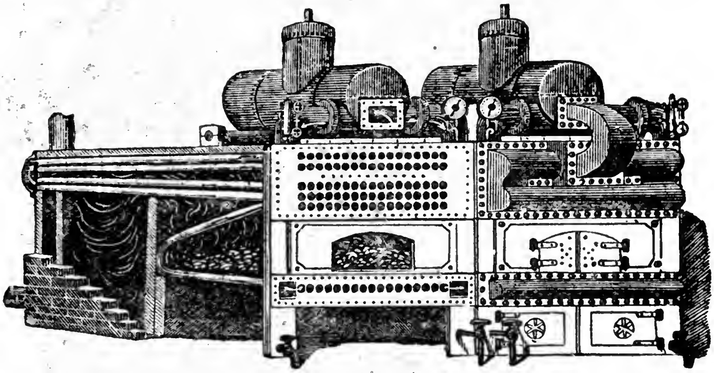


FIG. 207.

and 23841), 1894 (No. 16472), 1898 (Nos. 13031 and 18166), 1900 (No. 1382). These show the working out of the tube head design and other important details.

The Phleger Boiler.—The Phleger boiler is of American origin, and possesses some distinct features from other horizontal tube boilers. The fireplace, including the bars, is constructed (except at the two sides) entirely of tubes 2 inches diameter, laid flat to form fire-bars, and then bent up from the back of the grate at an angle to form the roof of the fireplace. At their lower ends they are expanded into a narrow strip of plate, which, with a cover semi-circular in section, forms the feed connection. The top ends lead into a similar chamber, in which there are also the ends of other two rows of horizontal tubes, which tubes extend

back as far as is required. Above these are other two rows of horizontal tubes connecting with another chamber in front, from which a branch leads to the steam drum above. The connections of the tubes place them in series, except that the steam and water from the one row below and above the fire pass through the upper four rows in pairs—the lower pair taking the current to the back and the upper to the front of the boiler. The boiler is illustrated in Fig. 207.

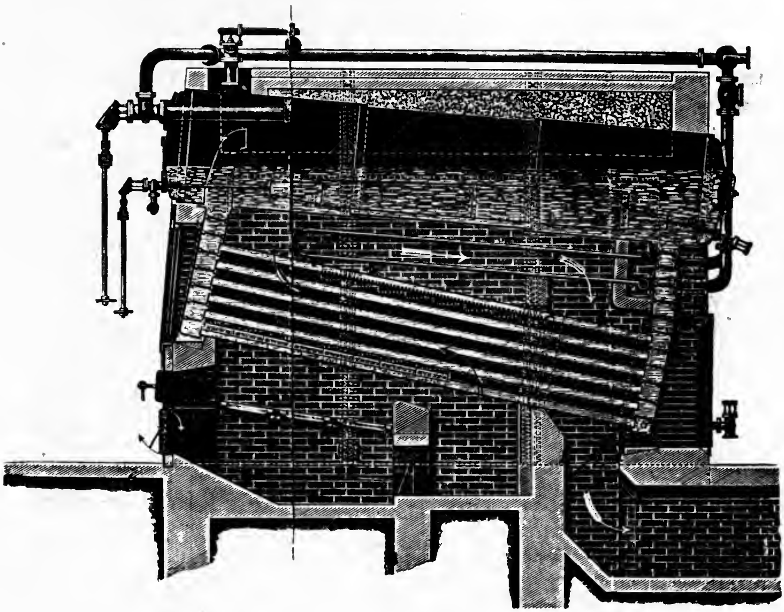


FIG. 208.

This boiler figured in the tests made at the American Institute Exhibition in 1871, but it does not appear to have been introduced into Britain.

Heine Boiler.—The Heine boiler is used in both Germany and America. It was patented in Britain by F. C. Glaser, for H. Heine, in 1881 (No. 3181), but does not seem to have been adopted to any extent here. It is shown in Fig. 208, and is one of the horizontal water-tube boilers with water-legs or chambers riveted to each end of cylindrical steam and water shells. These

shells range from 24 to 48 inches diameter, and for all sizes above 200 H.P., two shells are used, a steam drum being in that case placed above and across the front ends of these two cylinders.

Poole Boiler and Seaton Boiler.—The Poole boiler, also introduced in America, Fig. 209, shows the same general design, with the water-legs attached to one cylindrical vessel or drum, whilst other modifications are seen in the boiler proposed by Mr. A. E. Seaton in 1893 (No. 19853), as described by Mr. J. T. Milton in

FIG. 209.

Trans. Inst. N. A., 1894, and shown in Fig. 210, in the Lagrafel D'Allest boiler and the Oriolle boiler.

Lagrafel D'Allest Boiler.—The Lagrafel D'Allest boiler, as now used in the French Navy, is the outcome of numerous improvements, the original boiler having been introduced there about the year 1869. The modern Lagrafel D'Allest boiler was patented in England in 1888 (No. 11160), whilst the dates of French improvements are recorded in M. Bertin's "Marine Boilers," p. 249. Fig. 211 illustrates this boiler.

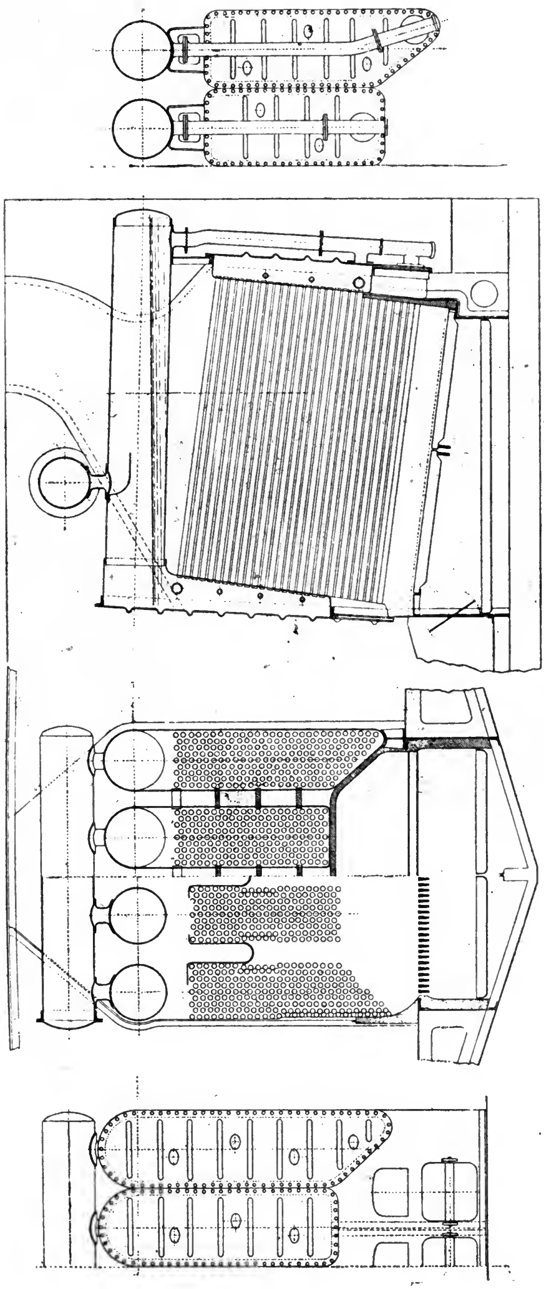


FIG. 210.

Oriolle Boiler.—The Oriolle boiler is also of French origin, and is used in the French Navy. The British patents are dated

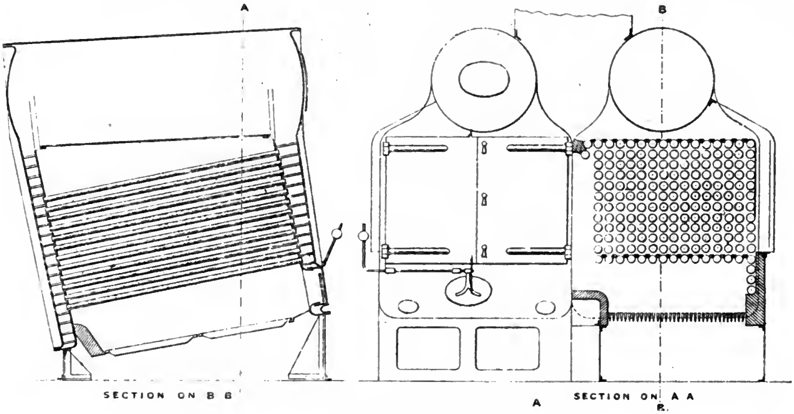


FIG. 211.

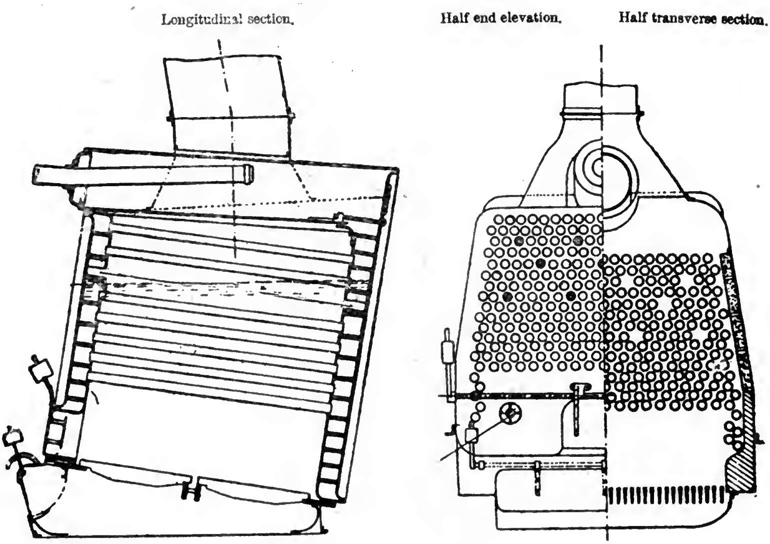


FIG. 212.

27th June, 1887 (No. 9121), and 18th April, 1890 (No. 5922). It is illustrated in Fig. 212, which shows the form used in French torpedo boats.

The Kelly Boiler.—An American boiler of this name ("Kelly") is described by Mr. D. K. Clark in "The Steam Engine," &c., and appeared amongst the boilers tested at Philadelphia in 1876. Its wrought iron horizontally inclined tubes were screwed into a cast iron header at the front end and closed at the back end, towards which they inclined downwards. See Fig. 213. The tubes had each a diaphragm plate inserted internally in order to ensure circulation of water in them. There seems, however, to be another water-tube boiler known as Kelly's boiler, or as the "National" boiler in America. This one has headers at both ends of the horizontally inclined tubes, somewhat after the Babcock and Wilcox and similar designs. This boiler seems

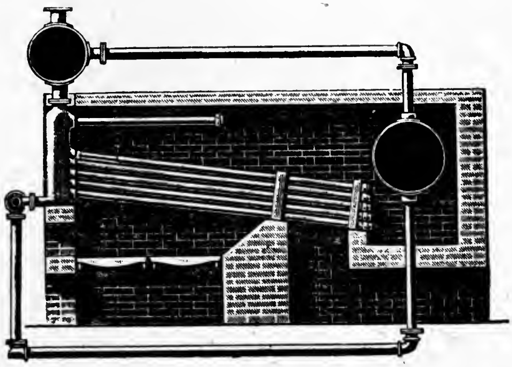


FIG. 213.

to have been patented in Britain in 1886 (No. 12697) and 1887 (No. 11141).

Dürr Boiler.—The boiler made by Messrs. Dürr and Co., of Ratingen, has some features in common with the former of the Kelly boilers, as well as with those of Alban, Lane, and Niclausse. The horizontally inclined tubes are connected only at the front end to a "header," which is a water chamber extending over the front of the boiler. This chamber is divided internally into two parts by a movable diaphragm plate which is formed of several pieces, each being secured in place by means of nuts threaded on screws formed on the stays. The horizontally inclined tubes are closed at their lower ends, where they are slightly reduced in diameter, by end plates fitting with conical joints and kept in

place by bolts. Internal concentric tubes are fixed to the diaphragm plate and communicate with the front division of the water chamber. These internal circulating tubes reach to nearly the end of the larger tubes, and as the normal water-level of the boiler is at about the centre of the steam chamber above, the circulation of water is similar to that of the Niclausse boiler. Figs. 214, 215, 216, and 217 show this boiler. At the sides, the water-tubes are bent so as to bring them together to form a water wall, and above the water level two or three rows of concentric tubes are employed as superheaters for the steam. This boiler was fully described by Mr. J. T. Milton in Trans.

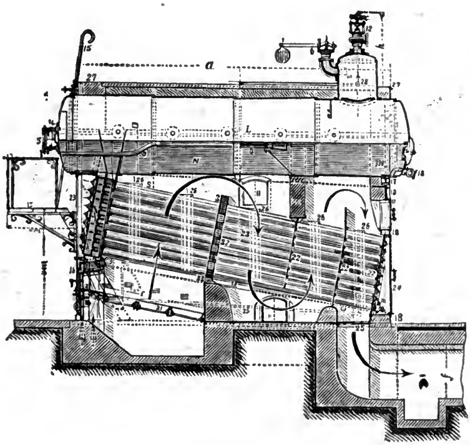


FIG. 214.

Inst. N. A., 1894. English patents for the Dürr boiler are dated in 1886 (No. 17123), 1888 (No. 12060), 1889 (No. 13222), and 1890 (Nos. 6398 and 19082), 1893 (No. 14745), 1895 (No. 1716), 1896 (No. 24787).

As made by the Société Industrielle de Paris, the Dürr boiler has some improvements in details, and is furnished with a feed-heater. It shares with the Niclausse boiler the feature of being able to do without expanded or other tube joints, the steam pressure tending to hold the tubes firmly in position and to tighten the joints.

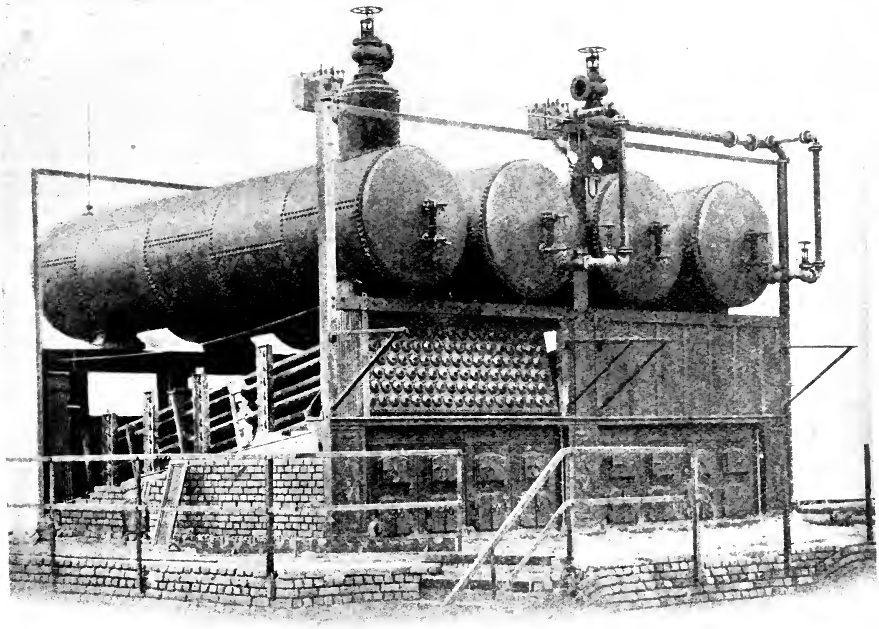


FIG. 215.

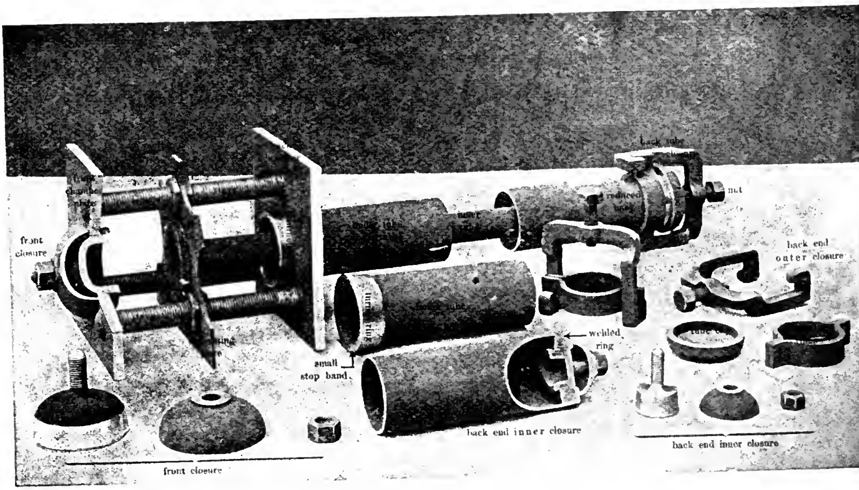


FIG. 216.

The Hornsby Boiler.—The Hornsby boiler, which was previously known as the Mills boiler, has some excellent features,

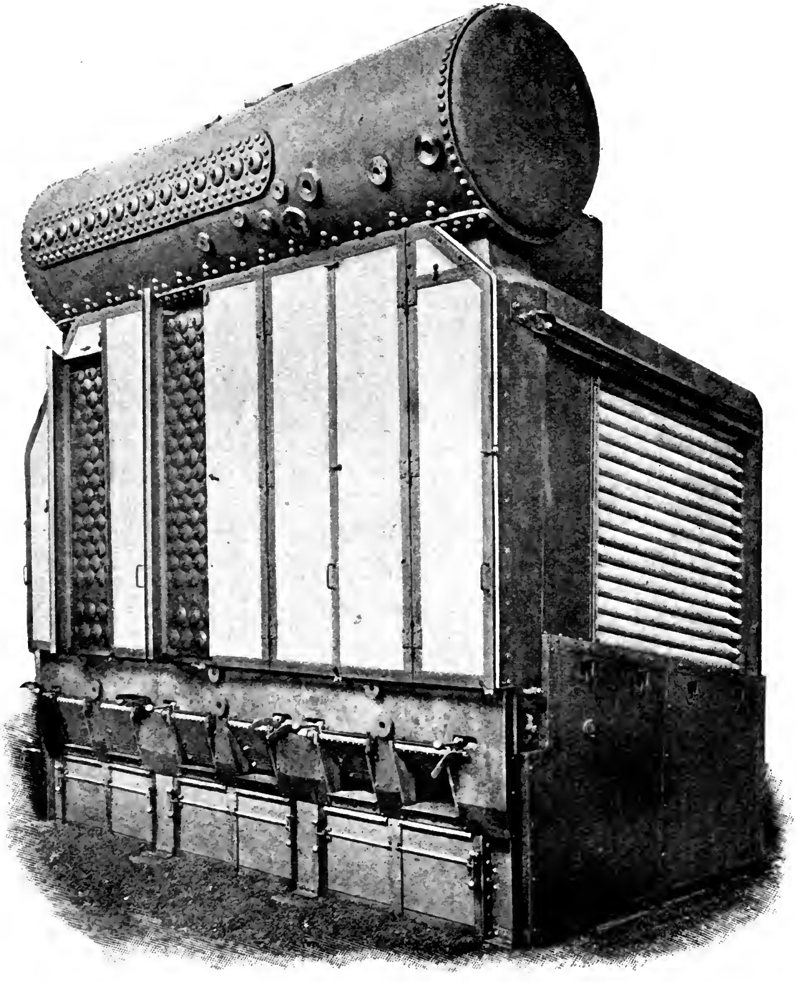


FIG. 217.

and is made either with a brick-lined or a water-lined furnace, according to the class and quality of the fuel to be used. The horizontally inclined tubes are fastened into wrought steel

headers which are formed by hydraulic pressure from mild steel plates, and the openings opposite the tube ends are

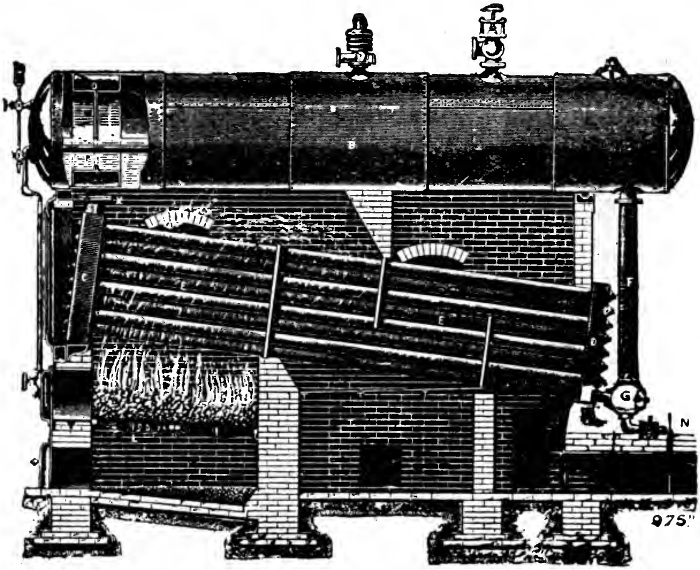


FIG. 218.

closed by internal safety hand-hole doors of mild steel with external caps. The cylindrical steam and water drum surmounts the tubes, and the vertical tubes connecting it with the headers allow freedom of expansion in the generating tubes. Figs. 218 and 219 represent this boiler.

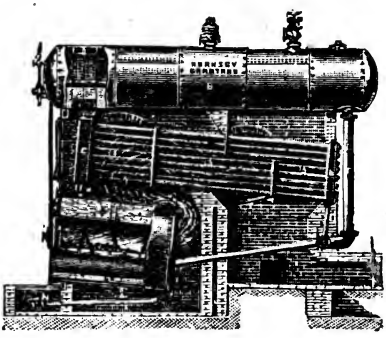


FIG. 219.

The British patents for this boiler are dated in 1888 (No. 7077), 1889 (Nos. 9938 and 11488), and 1893 (No. 949).

The Towne Boiler.—The Towne boiler has two sets of inclined tubes, which are inclined alternately from side to side across the

top of the fire, and are connected to flat chambers which are bent at the centre of their height in order to meet the incoming tubes at right angles. Fig. 220 shows this boiler, which has been introduced into launches and gunboats in America, and was patented in Britain in 1890 (No. 5064). There appear to be other boilers claiming the same design, as one similar to Fig. 220 was illustrated in *Electrical Industries*, a

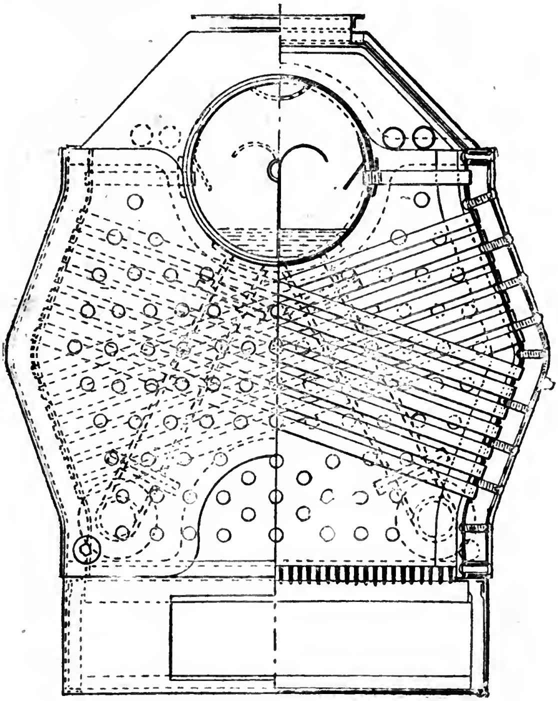


FIG. 220.

New York paper of December, 1892, Vol. iii., No. 12, under the name of the Worthington patent sectional water-tube boiler, manufactured by the New York Safety Steam Power Company, and patented in Britain in 1894 (No. 16750). A modification of this type of boiler was patented by A. Montufet in January, 1897 (No. 429).

Rainey's Boiler.—The only other boiler of this class which we illustrate here is the one patented by F. E. Rainey in 1896 (No.

2428). Fig. 221 shows this design, from which it will be seen that, in addition to the horizontally inclined tubes arranged in

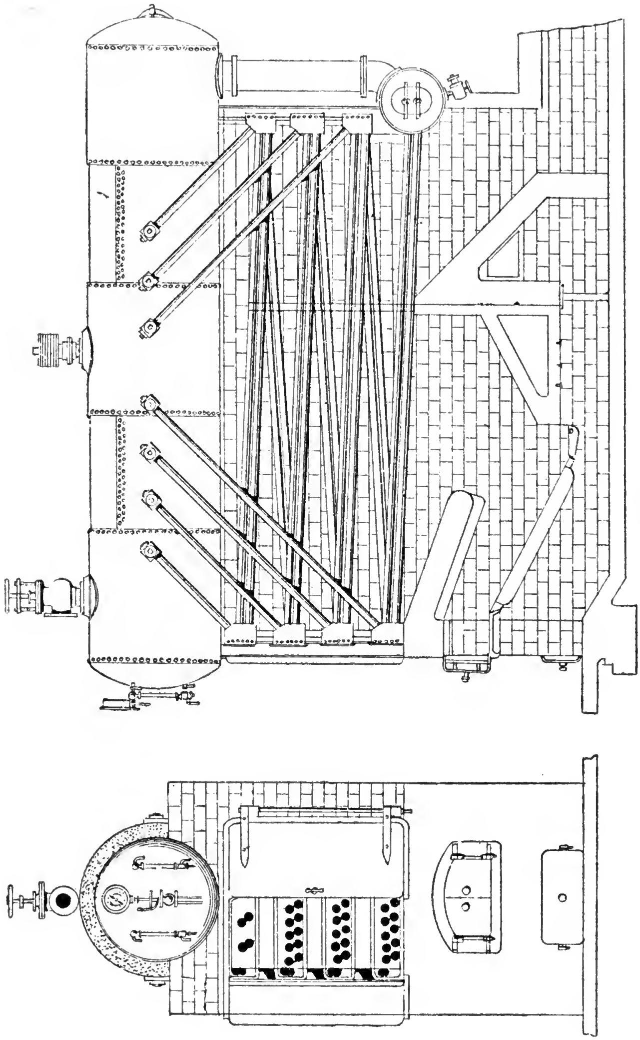


FIG. 221

headers, so as to form a flattened spiral, there are "riser tubes," one from each header, going directly to the steam chamber, and

allowing the steam brought into the header to escape upwards, while the water flows on through the horizontal tubes.

The horizontal form of the Peterson boiler will be found later (see p. 463).

Modifications of the Horizontal Tube Boiler.—The modifications of the horizontal water-tube boiler which have been proposed are too numerous to be noticed in detail. Amongst the more important of these are the boiler of G. Sinclair, patented in 1872 (No. 3726) and 1873 (No. 3693), which was made for some years at Albion Boiler Works in Leith, Scotland, and was described by D. K. Clark in his "Steam Engine," &c., Vol. ii., p. 772; Griffith's boiler, patented in 1873 (No. 2170), as made by J. Halliday in Manchester; Yarrow's boiler of 1879 (No. 316); Lloyd's of 1884 (No. 11633); the De Naeyer boiler of 1886 (No. 2769), introduced and manufactured in Belgium; Sellers of 1891 (No. 20954), which was introduced in America, and is illustrated in *Electrical Industries* of New York, Vol. iii., No. 12, p. 329; Anderson and Lyall's, patented in 1892 (No. 12609), described in Mr. J. T. Milton's paper "On Water-tube Boilers" (Trans. Inst. Naval Architects, 1894); the Coignet[1] boiler, patented in 1892 (No. 15168), and 1893 (No. 5145); the Zell boiler and the Gill boiler, both shown at the Chicago Exhibition in 1893, and illustrated in the *Engineer*, August, 1893 (pp. 118-170).

The Charles and Babillot boiler, illustrated in Bertin and Robertson's "Marine Boilers," p. 281, which was patented in Britain in 1891 (No. 16565), is a novel arrangement of concentric tubes horizontally inclined.

In addition to these and many similar designs there are several boilers having a single header or vertical water chamber with horizontally inclined tubes bent so that both ends of the tubes are connected to it. Of this design are the boilers patented by A. Greenwood in 1877 (No. 168), A. R. Thirion in 1890 (No. 8987), and E. A. Mayer in 1892 (No. 13192). The Solignac boiler, illustrated in the *Mechanical Engineer*, Vol. i., p. 600, is another example,[2] and an elaborate modification of this design is known as Petit and Godard's boiler, and is

[1] See Min. Proc. Inst. C. E., Vol. cxiii., p. 431; Le Genie Civil, Vol. xxii., 1893, p. 395.

[2] The Solignac boiler was patented in Britain in 1894 (No. 20466).

illustrated in Bertin and Robertson's "Marine Boilers," p. 265, but the original was, according to M. Chasseloup-Laubat, introduced by M. Sochet in 1855.[1] The comparatively recent Thornycroft-Marshall boiler, Figs. 222 and 223 belongs to the same class.

Such designs as that of J. M. Stratton, of 1890 (No. 5633), although special, may also fall within the class of horizontally inclined water-tube boilers.

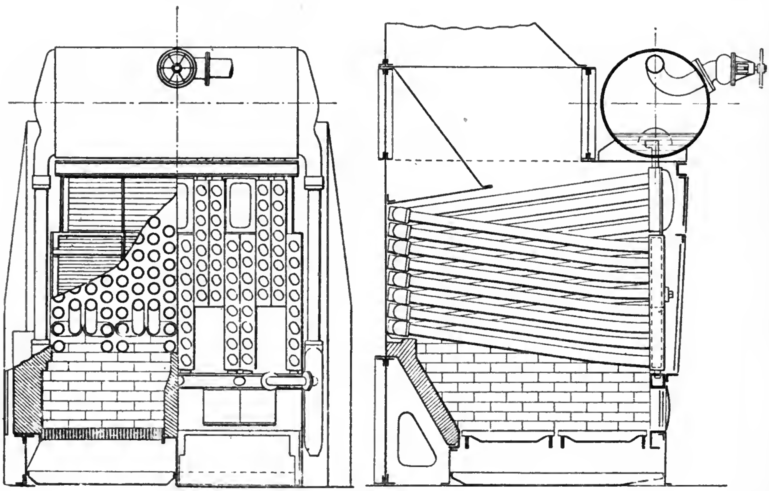


FIG. 222.

Horizontal Chamber Boilers.—Allied to this class are boilers formed of a number of horizontal cylindrical chambers connected together, usually by means of short vertical branches or tubes. This design is, in fact, a development of that of Woolf, but the number of tiers of chambers of comparatively small diameter has been increased since his day, and cast iron, as the material of construction, has been abandoned. Instances of this design are to be found in the boilers proposed by J. Brayshay in 1856 (No. 1738), L. Durand, 1858 (No. 1063), J. Howden, 1860 (No. 2854), B. Illingworth, 1876 (No. 3460), 1879 (No. 1563), J. C.

[1] See Les Chaudieres Marines, by M. L. De Chasseloup-Laubat. Paris: 1897, pp. 11, 72. Also Bertin and Robertson, p. 293.

Mewburn, 1880 (No. 2348), G. H. Lloyd, 1881 (No. 5741), and others.

The boiler patented by Mr. Howden was illustrated by him in his paper "On the Comparative Merits of Cylindrical and Water-tube Boilers for Ocean Steamships," in Trans. Inst. Naval Architects for 1894 (Plate lxiii., Figs. 7 and 8), and similar boilers were also subsequently introduced for land use by Messrs. Hawksley, Wild and Co., of Sheffield; Thomas Piggott and Co.,

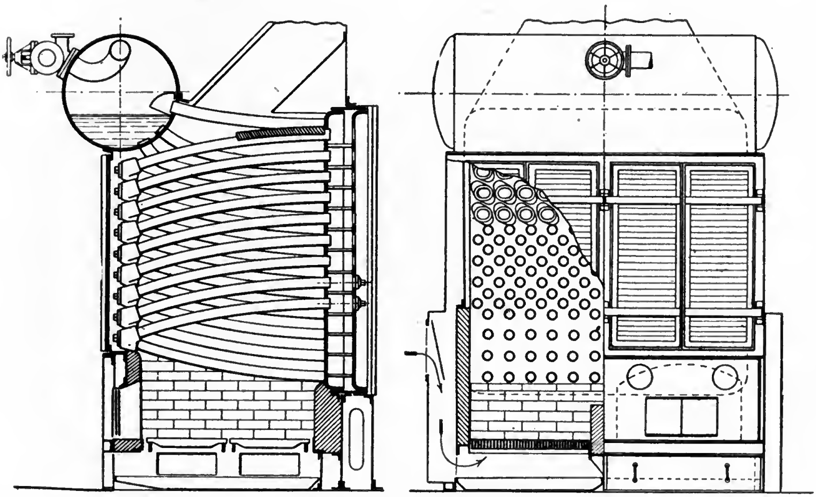


FIG. 223.

of Birmingham; and the Crosland Company of Manchester,[1] illustrations of whose boilers will be found in *Engineering* of 1874 and 1875. What may be called an exaggeration of this design, simply, however, on account of the increased diameter of the chambers, will be seen in the so-called "Howard" boiler constructed at Barrow for the steamer "Red Rose," this boiler being illustrated in Mr. Flannery's paper in Min. Proc. Inst. C. E., Vol. liv., p. 123 (in Figs. 3 of Plate 6); and in the Wigzell

[1] The patents of Hawksley and Wild are—1869 (No. 2922), 1872 (No. 3207), of the Kesterton boiler, 1872 (No. 3870), 1873 (No. 2497), and of the Crosland boiler, 1869 (No. 2083), 1870 (No. 2818), 1871 (No. 2749), 1872 (Nos. 1962 and 3310), 1873 (Nos. 1249 and 2614).

boiler, described by the same author in Trans. Inst. Naval Architects for 1876[1] (Vol. xvii., p. 274, Fig. 14).

Another arrangement of horizontal cylindrical chambers which has had many advocates is that in which the chambers are placed concentrically. A glance through the records of the Patent Office shows that this was from early days a favourite plan. It was, perhaps, suggested by Trevithick's boiler of 1802, which was subsequently known as the "Cornish" boiler; and, in fact, that boiler shows the plan in its most simple form, but it has been developed so that several thin layers of water are exposed to heat, in order to facilitate evaporation. A typical example of this design, and what was perhaps the latest attempt to utilise the plan in marine work is found in Howden and Morton's boiler, which was fitted in the s.s. "Ailsa Craig" in 1859, and is described in Mr. Howden's paper in Trans. Inst. Naval Architects for 1894 (Vol. xxxv., Plate lxi., Figs. 5 and 6).

Vertical Water-Tube Boilers.—The natural action of boiling, with the vertical ascent of the heated water and steam bubbles, doubtless suggested, at an early period, the suitability of vertical water-tubes for the construction of vessels in which such action was to take place. In the history of this design R. Trevithick's patent of 1815 (No. 3922) has been supposed to have introduced vertical tubes closed at the lower end and hanging by their upper end from a tube or water chamber, the pendant part being in the combustion space, but a careful study of that specification shows that it disclosed no such design. Trevithick had patented in 1831 (No. 6080) the use of a form of concentric vertical tubes, and others had previously brought out smaller vertical water tubes with concentric tubes, so that when Jacob Perkins followed in July of the same year with his patent (No. 6128) for the hanging tubes, each containing an internal tube open at both ends for water supply and circulation, only a small part of the main idea had been published by Trevithick.

From what is said by Tredgold ("The Steam Engine," 1st ed., p. 135; new ed., 1838, p. 128) it would appear that Count Rumford originated the hanging tube design, if not in the boiler which he put up in the Royal Institution in 1796, at any rate

[1] See also *Engineering* of 28th April, 1876.

in the model boiler which he presented to the French Institute in 1806, which latter Tredgold describes minutely. This, however, seems not to have been generally known either here or in France.

Perkins' idea was adopted successively by R. Prosser in 1839 (No. 7969), P. F. Joly in 1857 (No. 2443), and E. Field in 1862 (No. 2956), and 1865 (No. 2661), to the latter of whom is generally ascribed the credit of first forming the top end or "mouth" of the inner tube of a trumpet shape or conical form, the largest diameter being uppermost. In this country, consequently, such tubes are called "Field" tubes, but in France they are known as "Perkins" tubes, and in French works on boilers are shown both with and without the trumpet-mouthed inner tube.

There seems to be no reason why they should not be called "Rumford" or "Perkins" tubes in this country also. The only notable boilers in which these vertical or vertically inclined Perkins tubes have been used are those of Field, Allen, Wiegand, J. Thom and Phillips, although several other designs employing the same form of tube in a horizontally inclined position have already been noticed.

Clark's Boiler.—A. Clark proposed in 1822 (No. 4665) a boiler for high pressure constructed principally of vertical copper tubes slightly curved in their length to provide for expansion. The tubes were connected to a flat chamber below and to a "wagon-head" above, an arrangement which does not seem very well adapted for high pressure; but there were, however, distinct downcomer tubes provided between the two chambers, so that the design shows that the importance of water circulation was understood by some engineers at that early date.

The boilers of Joseph Moore, 1824 (No. 5032), and Paul Steenstrup, 1827 (No. 5580) followed, the latter having the tubes, set in a rectangular chamber, part of which was below the fire through which the tubes projected.

Eve's Boiler.—The boiler of Joseph Eve, 1825 (No. 5297) consisted of bent vertical tubes attached above and below to horizontal tubes of larger diameter, from which branches of similar diameter led into a steam chamber and a water chamber below. One form of it has been represented by the following figure, which is taken from Mr. G. Halliday's book on "Steam Boilers." Fig. 224.

Church's Boilers.—Wm. Church in 1832 (No. 6220) and 1833 (No. 6469), patented several forms of boilers employing vertical water tubes; but in the most notable of his boilers, which was used in the early days of steam road vehicles, these tubes were combined with vertical and horizontal chambers, so that the boiler was practically a vertical shell or tank boiler with vertical tubes and a water-cased furnace. An illustration of the boiler used in Church's steam coach will be found in the *Engineer* of

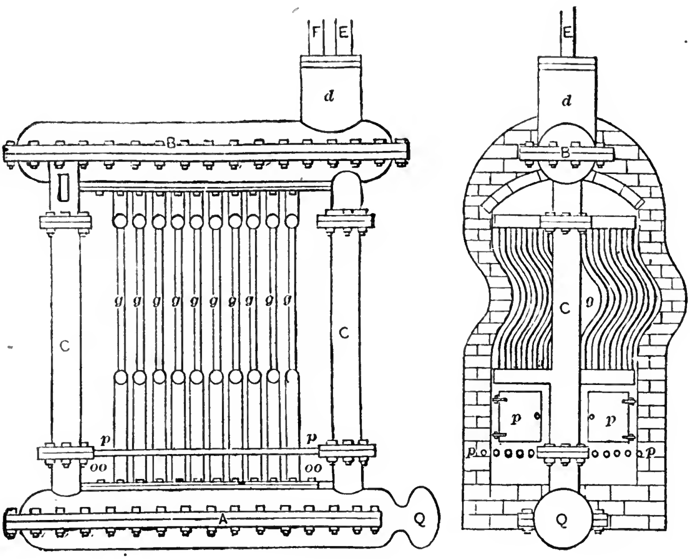


FIG. 224.

17th August, 1894, p. 154, where Sir Frederick Bramwell's paper on the subject of the early steam coaches is reproduced.

Summers and Ogle's Boiler.—W. A. Summers and N. Ogle in 1830 (No. 5927) brought out a boiler composed of vertical water tubes with concentric flue tubes inside. The water tubes were connected at top and bottom ends to transverse tubes of a flattened section, and the internal tubes were so fastened outside of the transverse tubes that they acted as stays or ties. Fig. 225 shows this boiler in vertical section.

W. A. Summers was afterwards associated with Andrew Lamb in the Lamb and Summers boiler.

Trevithick's Boilers.—R. Trevithick's patent of 1831 (No. 6082) cannot accurately be described as showing a boiler formed of concentric vertical water-tubes. It showed rather a number of concentric tubes grouped together to form fireplace, boiler, jacket, condenser, and air vessel. His patent of 1832 (No.

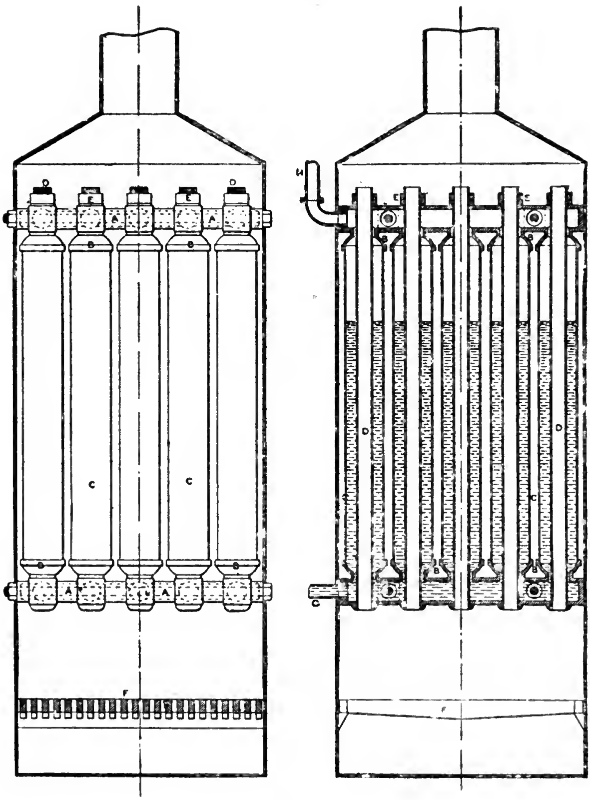


FIG. 225.

6308), however, contained an elaborate design for a vertical water-tube boiler, having vertical tubes set round the fire and connected top and bottom to tubular rings, the bottom ring being below the grate. Several **U**-shaped tubes were hung in the combustion space over the fire for the purpose of superheating the steam on its way from the outside ring of vertical tubes through the **U**-tubes to the engine.

Maceroni and Squire's Boiler.—John Squire and Francis Maceroni, first together in 1833 (No. 6449), and afterwards separately in 1839 (No. 8229), 1842 (No. 9564), took out patents for a vertical water-tube boiler with concentric inner flue tubes, the outer tubes being connected together by short horizontal

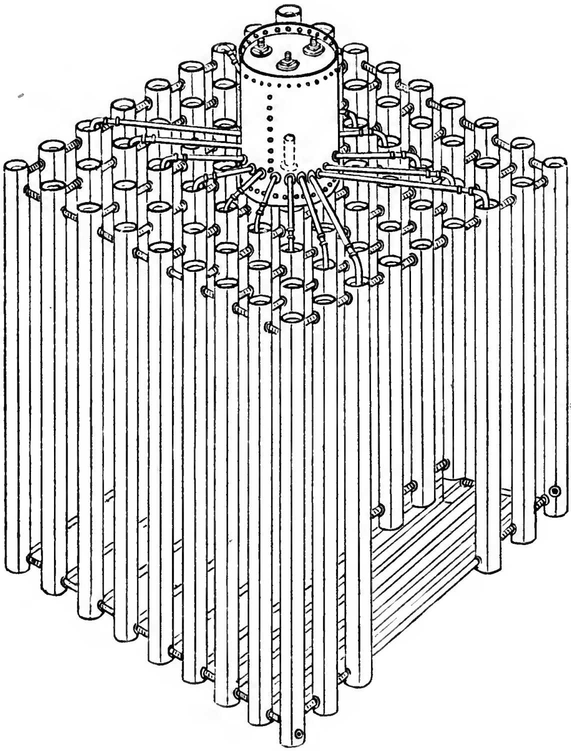


FIG. 226.

tubes. Fig. 226 gives an illustration of this design in perspective. In the later patents some improvements in details were proposed.

Other designs were proposed by J. McDowal in 1834 (No. 6606), W. Carpmael in 1835 (No. 6955), H. Elkington in 1837 (No. 7305), and F. Hills in 1839 (No. 7958), and 1840 (No. 8495), none of which demand particular notice.

James' Boiler.—In one of the patents of W. H. James, viz., that of 1838 (No. 7854), however, there was a design which seems to have been misunderstood by some. In this patent he proposed to use vertical zig-zag shaped tubes, or alternately spiral tubes, connected top and bottom to annular horizontal pipes. The vertical tubes were to be partly filled with coils of wire, with the idea of communicating heat more rapidly to the water in them. The mention of these coils has evidently caused some to imagine that this was a coil boiler, whereas its distinctive feature was the vertical zig-zag or spiral tube.

Craddock's Boiler.—In 1840 (No. 8432) and 1846 (No. 11473) Thomas Craddock took out patents for a vertical water-tube boiler which for a time gave fair promise of good results. As latterly made it consisted wholly of vertical tubes, with a small bend or curve in the upper part of their length to provide elasticity under expansion, these tubes being attached at each end to the flat side of a small **D**-shaped box or channel. The lower channel was used for water supply and the top one for conveying steam to a steam dome or to the engine. Figs. 227, 228, and 229 show this boiler, the two latter as arranged for marine use, in which form it had various trials in the s.s. "Thetis" about the year 1856. It is evident, however, that there was not sufficient freedom of circulation of water provided for by the **D**-shaped connections, and that this action is further hindered by the want of sufficient downcomer channels. Consequently serious alterations were required in the original "Thetis" boilers, but with these excellent evaporative results were obtained until corrosive action destroyed the vertical tubes.

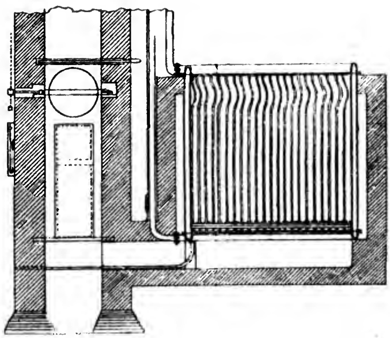


FIG. 227.

In 1852 (No. 51) and 1857 (No. 931 and No. 1162) Craddock turned to other forms of boilers, but was not successful in getting them introduced. One form of his boiler of 1857 is, however, similar to that of some recent ones.

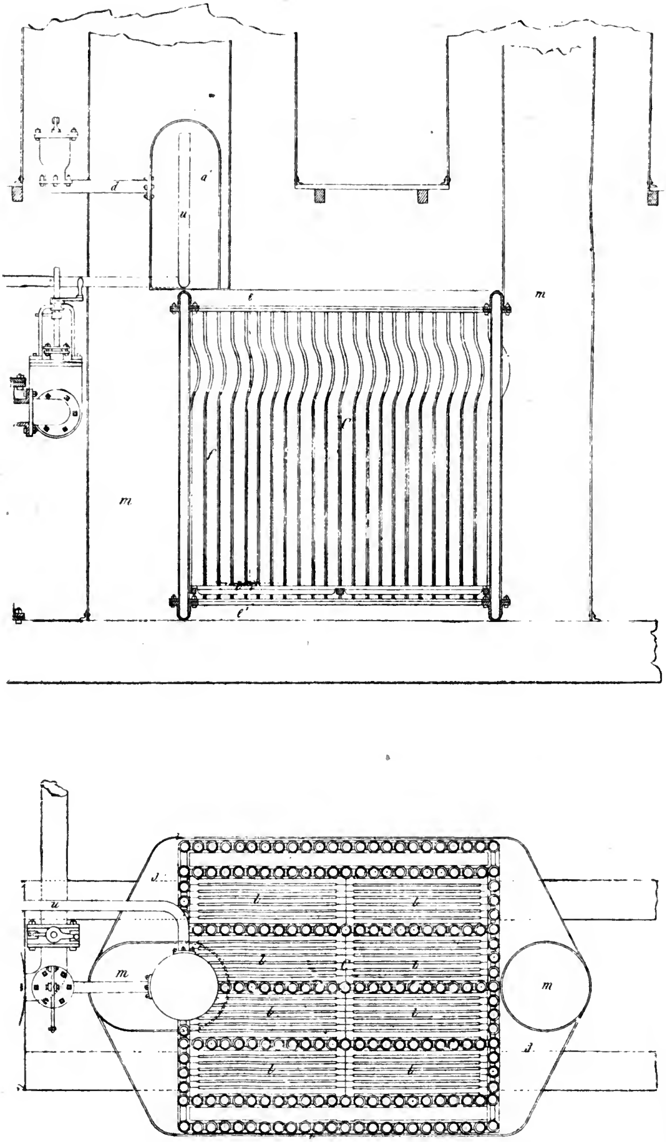


FIG. 228

Clarke and Motley's Boiler.—The patent of J. Winchester, 1842 (No. 9560), calls for no further mention, but that of Thos. Clarke and Thos. Motley, 1849 (No. 12514), although never introduced into use, has come into some notice in recent years through abortive attempts to find in it the original of a design which it does not represent. This boiler was formed of a main vertical cylindrical chamber, from which at the bottom two semi-circular or **D**-shaped branches extended, one on each side of the fire and just below the fire-bars. A single chamber of the same form, but of larger dimensions, branched off some distance above, and these branch chambers were connected by two groups of straight water tubes inclined a little from the vertical, one group being on each side of the fire. The two rows of tubes nearest to the fire were of larger diameter than the rest, of which the diameter was decreased as the rows receded from the fire. The Fig. 230 illustrates the form proposed for this boiler. It was evidently intended to have a supplementary fire under the lower branch chambers, and a fan was provided at the bottom of the ash-pit, in which this supplementary fire is shown, to supply air for combustion. The spindle carrying this fan passed right up the centre of the main vertical chamber, and it carried paddles for forcing the water into the lower branches, in addition to a fan with curved blades in the steam space for drawing off the steam and passing it out into steam pipes. This boiler bore more resemblance to the one subsequently patented by W. Johnson in 1855 (No. 35) than it does to boilers of the three-chamber type introduced in 1876 and in subsequent years.

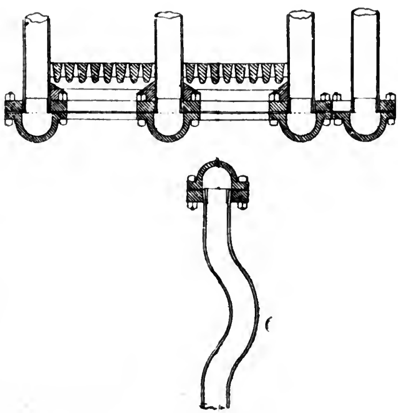


FIG. 229.

Johnson's Boiler.—Fig. 231 shows Johnson's boiler, which requires no description.

The patents of W. E. Newton, 1849 (No. 12783), W. Warne,

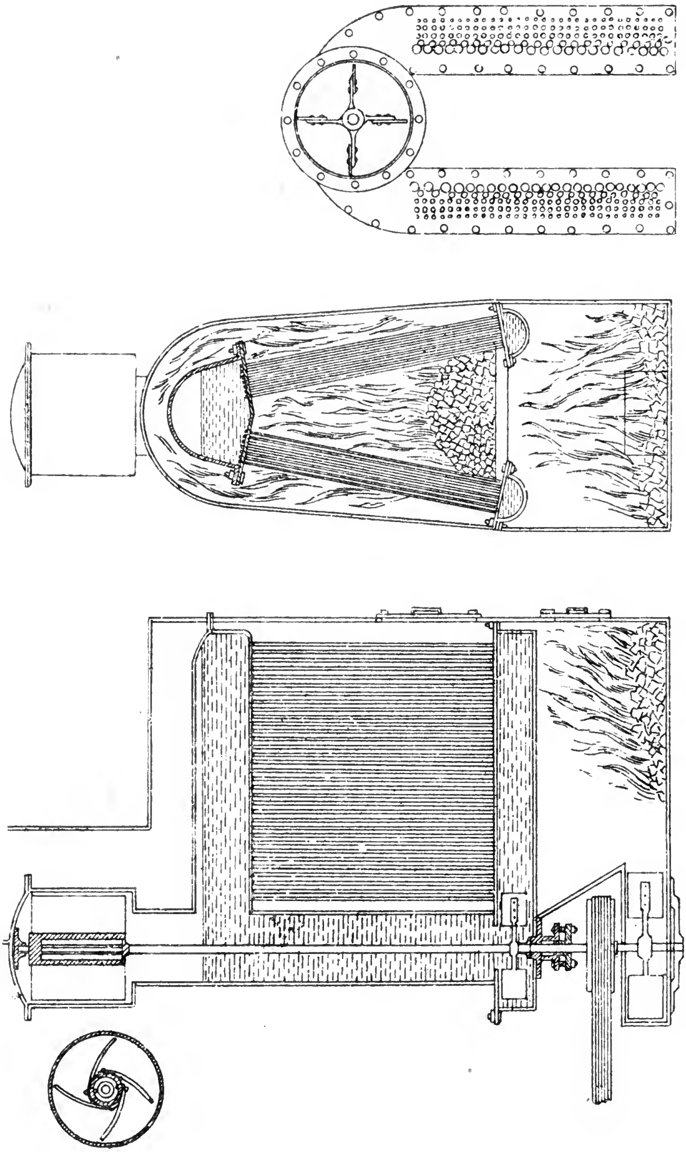


FIG. 230.

1854 (No. 558), J. McFarlane, 1854 (No. 1202), L. N. Langlois and J. B. Claviers, 1854 (No. 1890), John Elder, 1858 (No. 162), and J. Willcock, 1859 (No. 2614), all describe boilers of the vertical water-tube class, some of which possess interesting features, such as means for passing the currents of water and gases in opposite directions, tubes oval in section or tapering in diameter upwards, the increased diameter being above, combination of straight and spiral tubes, &c., but none of them requires more particular notice.

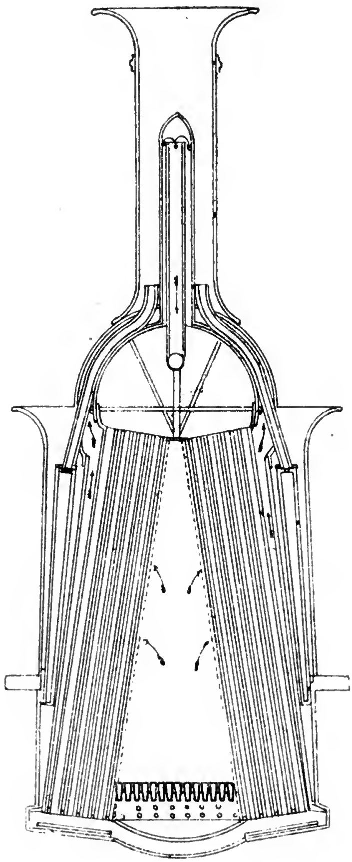


FIG. 231.

Rowan and Horton's Boilers.—In 1861 (No. 2207) J. M. Rowan and T. R. Horton patented a boiler composed of vertical water-tubes set in rectangular frames or leaves of square section, formed by channel irons and plates or by flat plates and angle-irons. These frames were set on edge across three cylindrical water chambers below, to which they were rigidly attached, and across their centre above a steam cylinder with vertical domes was placed, bent tubes from each side branching out horizontally from the steam drum and entering the top of the frames vertically. This design was a development of their cellular boiler of 1858 (mentioned later on p. 485), and is illustrated by Fig. 232.

A further development was patented in 1869 (No. 3253), in which the frames or leaves were entirely abolished, and the vertical water-tubes were connected directly to the steam and

water cylinders, into which all entered radially, the end portions of the tubes being bent to various arcs of a circle, according to their relative positions, for this purpose.

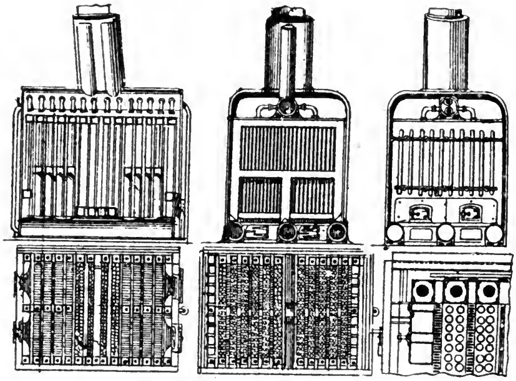


FIG. 232.

This design is illustrated in Figs. 233 and 234. It was fitted in the steamers "Haco," "Propontis," "Nepaul," "Bengal," and others, but on account of an accident to the boilers of the "Propontis," shown in Fig. 235, the exact cause of which is given in the author's papers in Trans. of the Inst. of Engineers

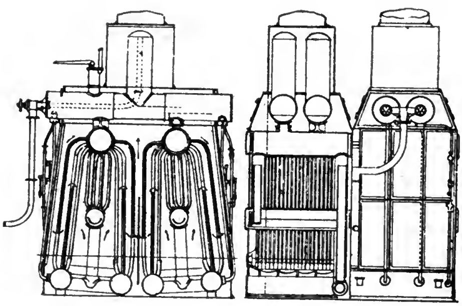


FIG. 233.

and Shipbuilders in Scotland, Vols. xxiii., pp. 73-117, and xli., pp. 117-121, the introduction of them was prematurely stopped.

This was undoubtedly the first boiler of any class in which numbers of small tubes are connected to cylindrical chambers

which they enter radially. This feature of construction has been widely copied since 1869.

W. E. Newton in 1859 (No. 895) and J. G. E. Larned in 1858 (No. 2803) both proposed vertical water-tube boilers which have some points of interest. The latter specification, though only a

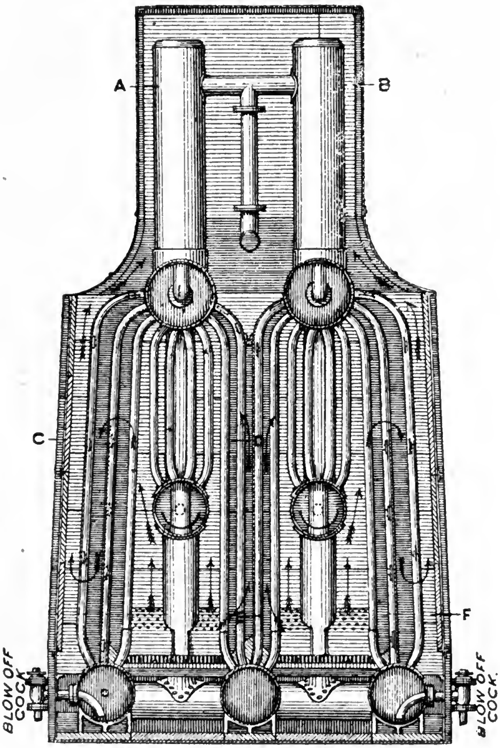


FIG. 234.

provisional, gives some figures of the dimensions of the boiler, which, it is said, had given 120 H.P.

Green's Boiler.—E. and E. Green in 1861 (No. 2671) patented a boiler composed of vertical water-tubes set in rows and tapered in a similar manner to that of Miller's cast iron boiler mentioned at page 365. The vertical tubes were corrugated on their outside surface in order to increase the area of heating

surface, and several rows farthest from the fire were used to heat the entering feed water, these tubes being furnished with similar scrapers to those used in Green's usual feed-heater or economiser.

Williamson's Boiler.—Several arrangements of a vertical water-tube boiler, the tubes inclining at a slight angle from each side

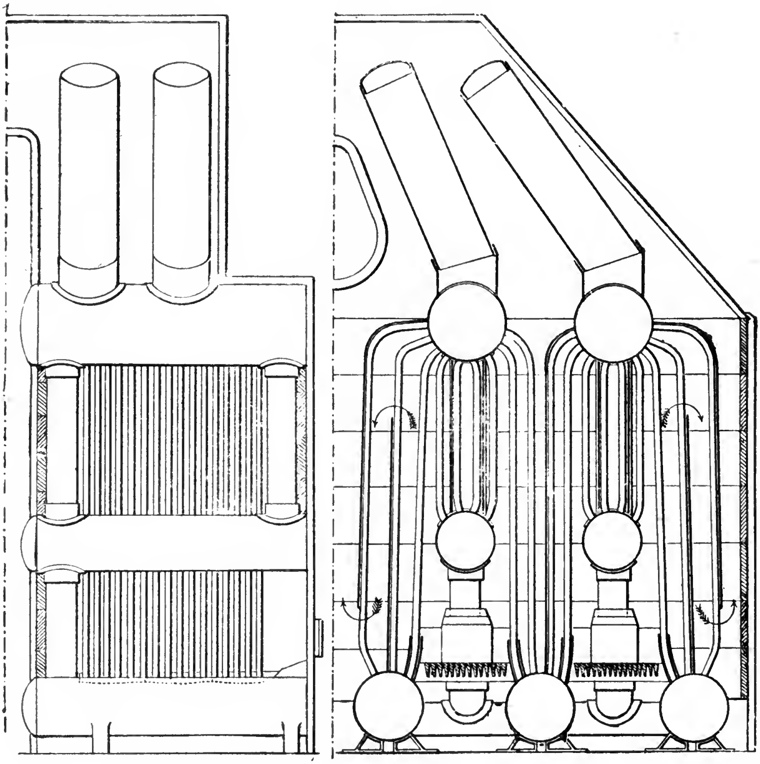


FIG. 235.

of the fire, were proposed by A. W. Williamson in 1861 (No. 2794) and 1862 (No. 619). The great point aimed at by Professor Williamson in these boilers was to have each tube free to expand without straining its connections, and with this object one end of each tube was closed and a smaller bent pipe attached it to the main steam connection. Figs. 236 and 237 illustrate this boiler, which was fitted into the steamer "Murillo,"

but was unsuccessful. An account of it is given by Mr. Howden in Trans. I. N. A. 1894, Vol. xxxv., p. 311.

Field's Boiler.—Several patents were taken out by E. Field, with some partners, in 1862 (No. 2956), 1865 (No. 2661), 1866 (No. 1694), and 1867 (No. 1419), for boilers employing the hanging tube invented by Jacob Perkins, with an internal tube of which the top end was conically shaped to form a "trumpet-mouth." In the first of these patents the application of these tubes to a vertical steam fire engine boiler is shown, but it is in the last of them that what is known as the "Field" boiler is set forth.

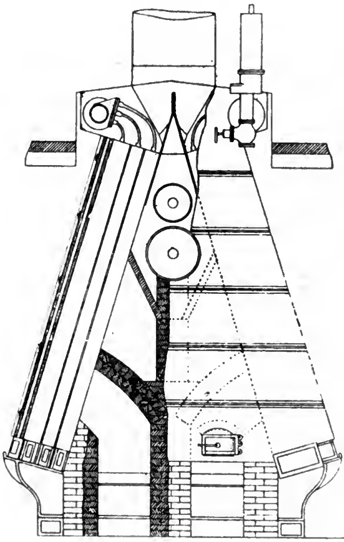


FIG. 236.

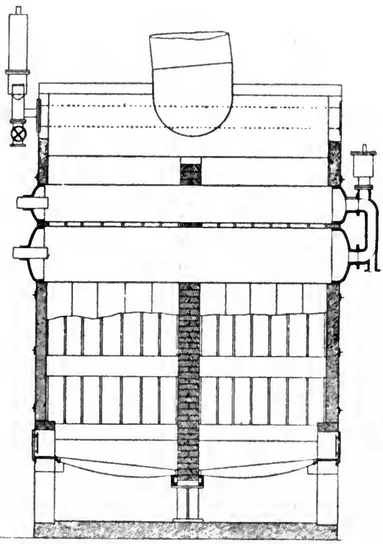


FIG. 237.

This boiler is illustrated in Fig. 238, and a description of it will be found in the discussion on a paper on water-tube boilers by Mr. V. Pendred in Trans. of the Society of Engineers, London, for 1867, whilst the earlier boilers with "Field" tubes are described by Mr. D. K. Clark in the "Steam Engine," &c., Vol. ii., p. 737, &c.

A somewhat similar design was proposed by A. V. Newton in 1864 (No. 1178), and the Kinsey "Unit" boiler, illustrated in *Engineering*, Vol. viii., p. 383-386, has some features in common with these designs.

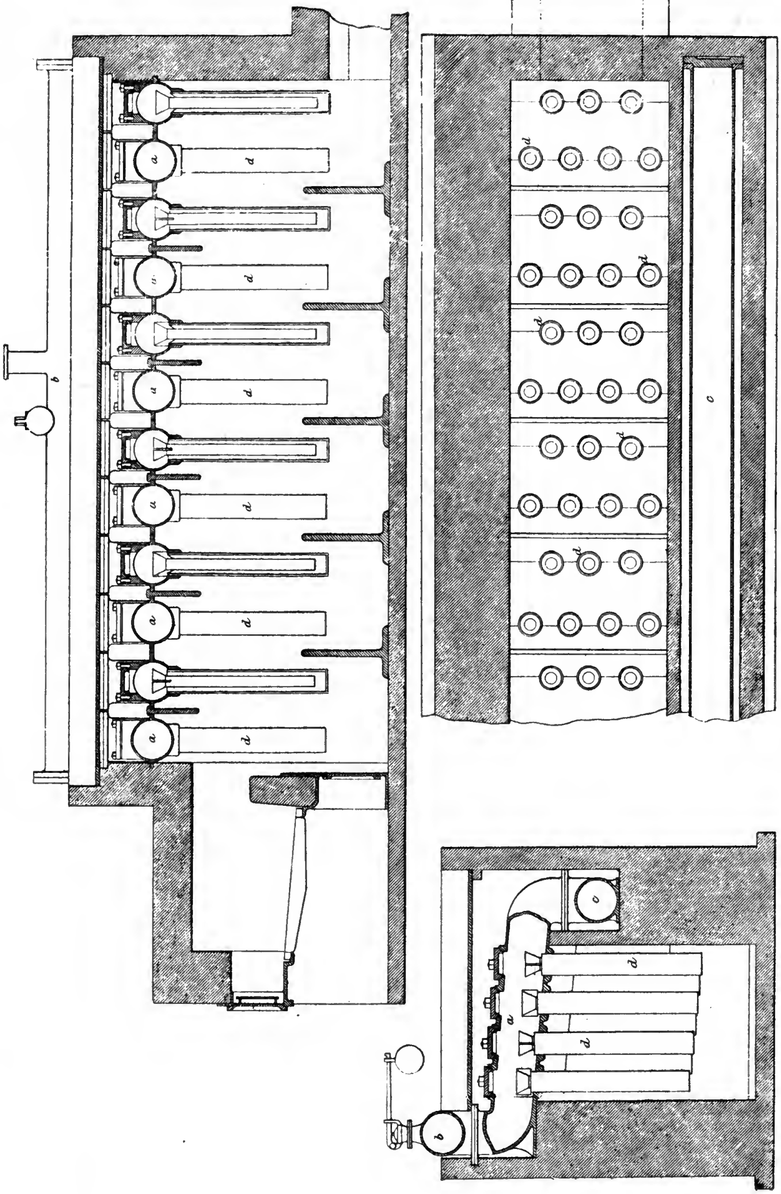


FIG. 238.

Twibill's Boiler.—Joseph Twibill in 1865 (No. 243) and 1866 (No. 2378) patented water-tube boilers constructed of vertically inclined tubes with different degrees of inclination. In one arrangement the tubes forming the fireplace were placed in the form of a triangle, whilst in the flue or main heating chamber they were ranged parallel to one another and joined at each end by horizontal pipes, with a water chamber and a steam chamber above the vertical tubes. Another form, illustrated in Fig. 239, had the tubes more horizontally inclined with vertical standpipes, and intermediate horizontal connections to which

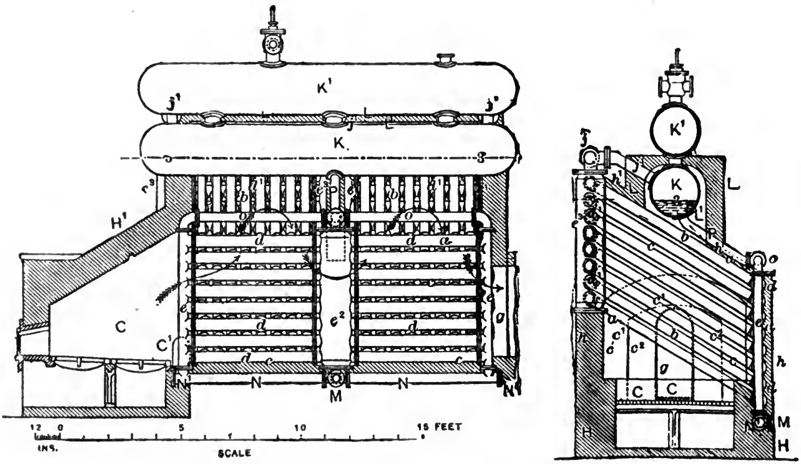


FIG. 239.

the ends of the tubes were attached. The fireplace was formed of brickwork, and the steam and water drums were carried by the end walls of the casing.

Jordan's Boiler.—The boiler patented by T. B. Jordan in 1865 (No. 2776) possessed some interesting features. It was composed of vertical tubes of 9 inches in diameter and 7 feet 6 inches long, made of lap-welded wrought iron $\frac{1}{4}$ inch thick, and having at the top and bottom ends a cast iron ring with side flanges to which water and steam branch pipes were attached. A wrought iron bolt tied the two caps to the tube; but it was this tie-bolt which, as in the case of the Harrison boiler, was most frequently objected to.

Fig. 240 illustrates this boiler. Each vertical tube was reckoned as equal to one H.P., and some testimony to the

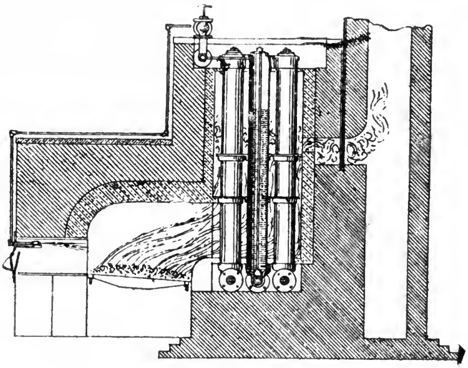


FIG. 240.

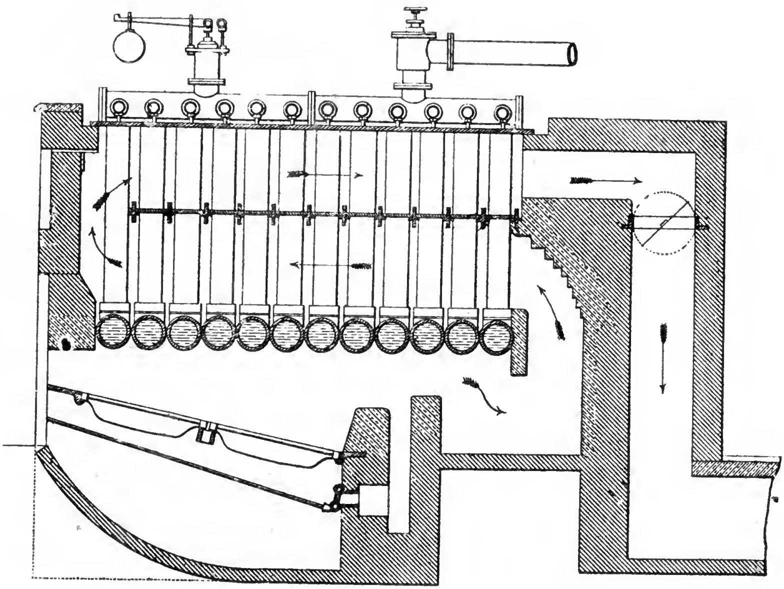


FIG. 241.

satisfactory working of the boiler may be found in the discussion on Mr. V. Pendred's paper on water-tube boilers, in Trans. of the Society of Engineers, 6th May, 1867.

Howard's Boiler.—Jas. Howard and E. T. Bousfield took out a number of patents for what was known as the Howard vertical tube boiler, manufactured and used at Messrs. J. and F. Howard's Britannia Works at Bedford. These patents are dated 1866 (Nos. 226 and 1811), 1867 (No. 76), 1868 (Nos. 430 and 3468), and later years, and the boiler consisted of vertical tubes, connected top and bottom by transverse tubes, and having concentric circulating tubes inside the vertical tubes extending up to the water level of the boiler. Figs. 241 and 242 show this

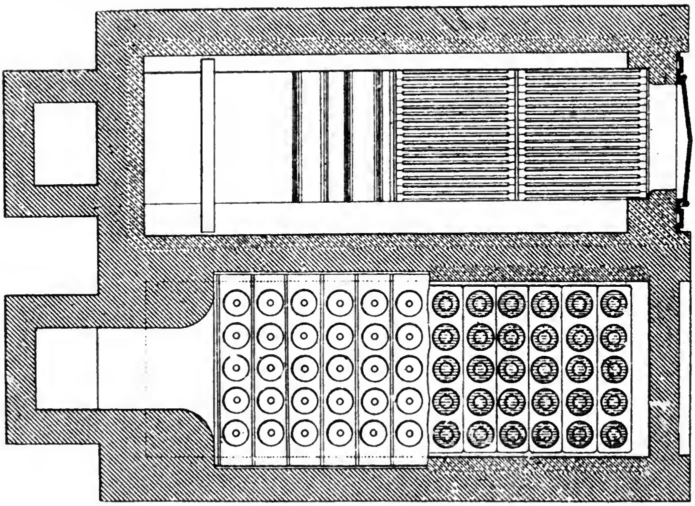


FIG. 242.

boiler, which gave fairly good results, some record of which will be found in Mr. Pendred's paper and discussion above quoted.

Although one section of the Howard vertical tube resembles the hanging tube of Perkins with its internal tube, it is evident that this design is only approximately similar to Perkins'.

Wiegand Boiler.—In the case of the Wiegand boiler, introduced in America, but patented in Britain in 1868 (No. 1365) and 1870 (Nos. 1856 and 3390), we have, however, a direct application of the Perkins tube. This boiler is illustrated in Fig. 243. It consisted at first of rectangular boxes, or small tanks, from which pendant tubes hung vertically downwards, each of these tubes having an internal tube provided with external fins

or feathers in order to cause the steam and water to ascend spirally, whilst the top of the internal tube was formed with a tapering or extended mouth so as to collect the revolving current of water and direct it into the tube. In the illustration, which shows the boiler as tested at the International Exhibition at Philadelphia in 1876, the form of the boxes or tube-heads was altered, as well as that of the internal circulating tubes.

In the boilers of C. M. Barker, 1869 (No. 1228), and of Rogers and Black, the latter of which was also tried at Philadelphia in 1876, and is illustrated in D. K. Clark's "Steam Engine," &c., Vol. i., p. 255, vertical water-tubes were combined with a cylindrical shell, in the one case inside and in the other outside of the larger vertical cylinder.

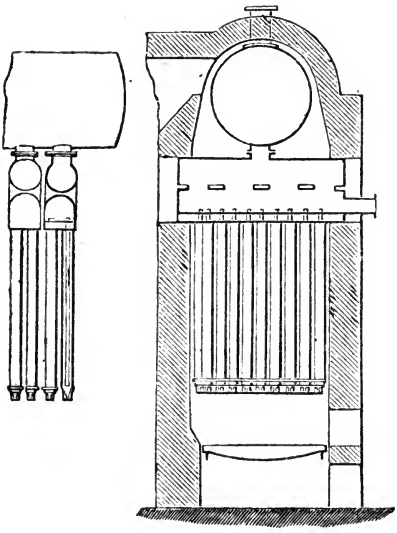


FIG. 243.

Firminich Boiler. — The Firminich boiler was also introduced in America, and was among the boilers tested in 1876 at Philadelphia.

Fig. 244 shows its form. It was composed of vertical water tubes, two rows of which were connected top and bottom to cylindrical chambers running from front to back of the boiler.

Fryer's Boiler.—A. Fryer patented in 1874 (No. 1774) a peculiar design of vertical tube boiler which is shown in the illustration, Fig. 245. It had three horizontal chambers above and four below, the centre one of the three above and the two inner ones below being of larger diameter than the others. Several rows of small water-tubes connected the upper and lower chambers, some of them being bent at one end and the others being straight, and large downcomer passages were also constructed between the three larger chambers. After the success of some of the three-chamber boilers, to be subsequently described, this

design was considerably altered, and in the discussion of a paper on "Torpedo Boat Destroyers," in the Institution of Civil Engineers (Min. Proc. Inst. C.E., Vol. cxxii., p. 81), Mr. D. Halpin put forward Fig. 246 as a representation of the boiler invented by Fryer. The contrast between the two is, however, too

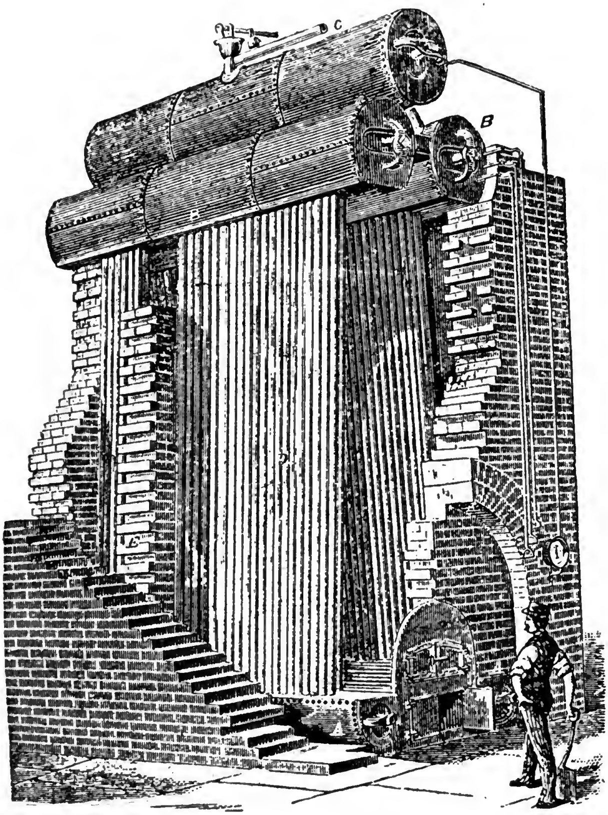


FIG. 244.

glaring to pass without notice ; but this is not the only design which has been subjected to some alteration in order to bring it into conformity with more modern ideas.

Rowan's Boiler.—In 1876 (No. 4430) the author of this work patented, as a development from the Rowan and Horton designs

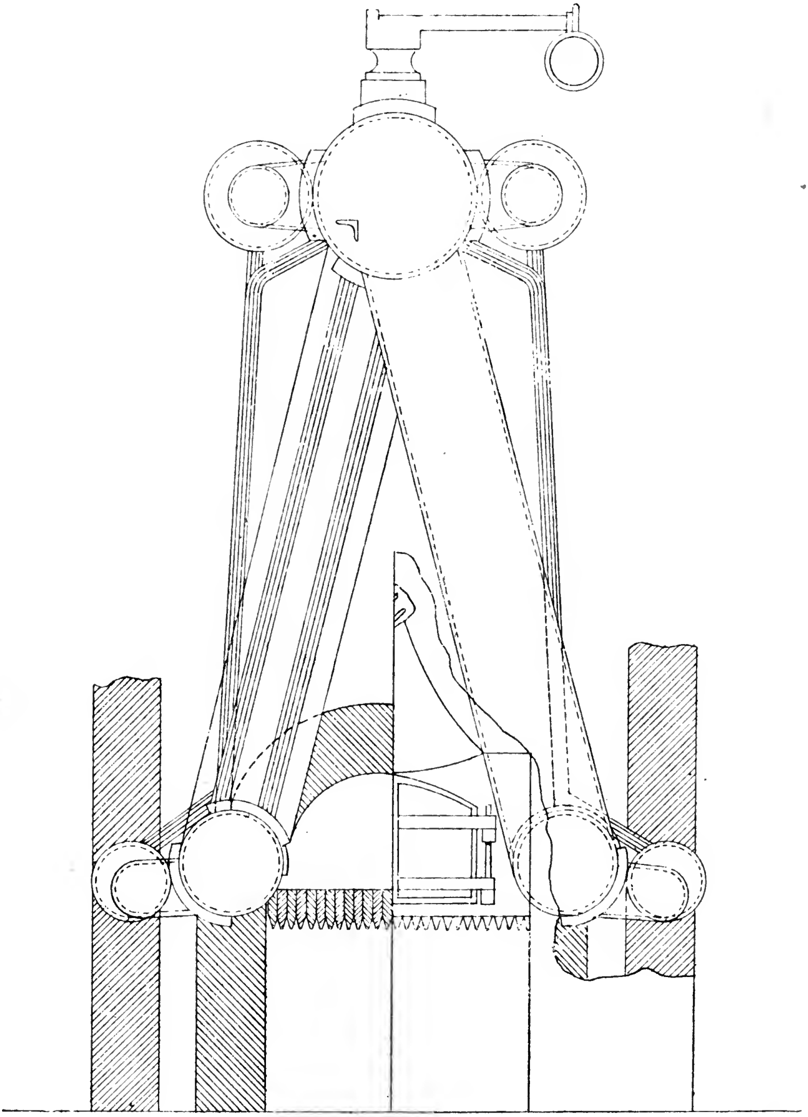


FIG. 245.

already referred to, and with a special view to the requirements of vessels of the Navy, a boiler composed of three cylindrical chambers, arranged horizontally one on each side of the fireplace and one above, so that lines drawn through their centres would form a triangle, with vertical water-tubes slightly inclined and having their ends bent to enter the cylindrical chambers radially. This boiler is illustrated in Fig. 247 and Figs. 52 and 53 (Chap. III.),

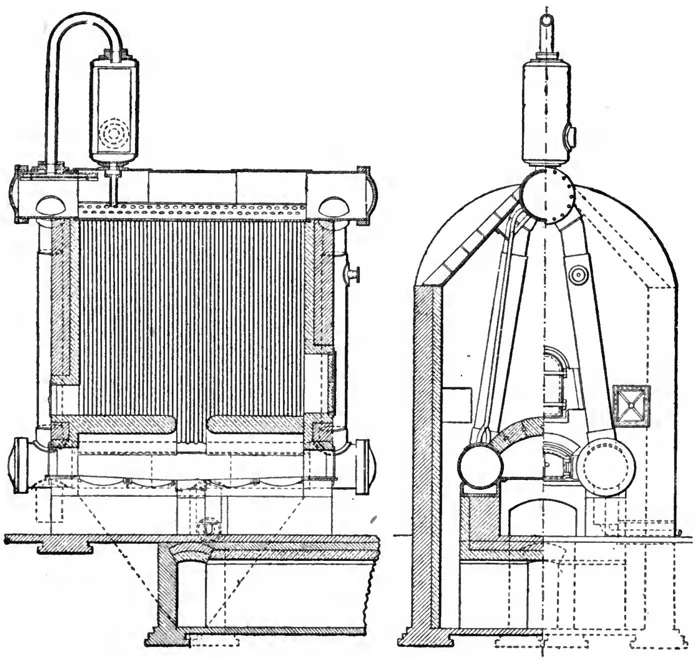


FIG. 246.

and it was undoubtedly the first of a type which in more recent years has become widely used, the three-chamber boilers of Yarrow, Thornycroft, Normand, Blechynden, Reed, Fleming and Ferguson, and many others being modelled on the same type with some differences in the shape given to the water-tubes joining the three chambers. Distinct downcomer tubes were at first common to all these boilers, but latterly Mr. Yarrow discarded these and preferred to utilise the outer rows of small water tubes for the downward currents of water.

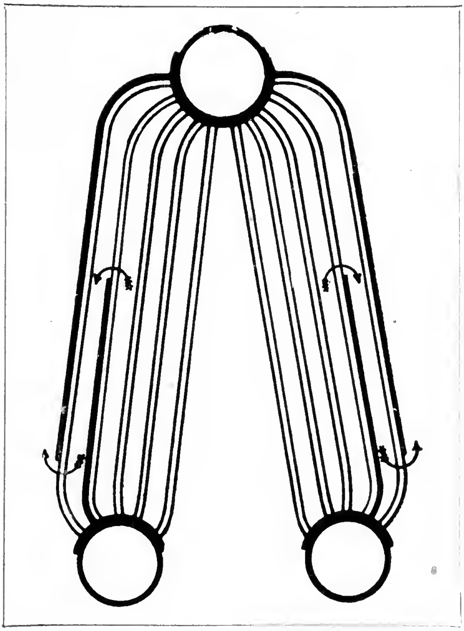


FIG. 247.

Thornycroft's Boiler.—J. I. Thornycroft's three-chamber boiler ("Speedy type") seems to have been patented in 1885 (No. 1404), although it was not brought prominently forward until some years later. It is shown in Figs. 248 and 249, and has been frequently described in his own and other papers. See especially Min. Proc. Inst. C.E., Vol. xcix., p. 41, and Trans. Inst. N.A., 1889. The tubes are bent so as to enter the steam chamber on the upper side above the water level. Mr. Thornycroft has also introduced another form of water-tube boiler, in which there are only two main horizontal chambers, and the water-tubes are connected to these in such a way that the outline of the boiler somewhat resembles that of a peg-top. This is known as the "Daring type," and is illustrated in Fig. 250. Descriptions of it and its work will be found in comparatively recent papers by Mr. Thornycroft and by Mr. J. T. Milton (Inst. C.E., Vol. cxxxvii. and Trans. Inst. N.A.). This form was patented in 1890 (No. 17809).

White's Boiler.—Another three-chamber boiler was patented by J. L. and H. S. White in 1889 (No. 6934), and 1893 (No. 18076).

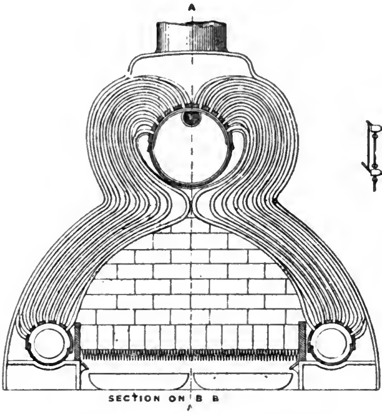


FIG. 248.

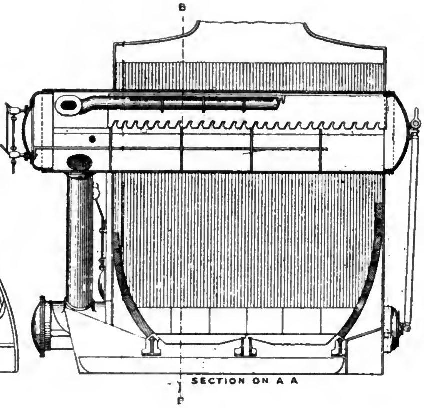


FIG. 249.

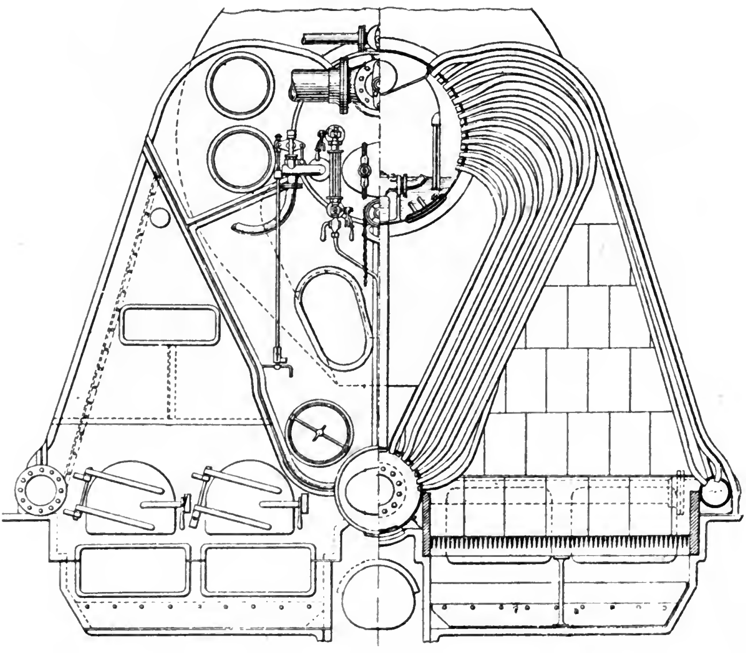


FIG. 250.

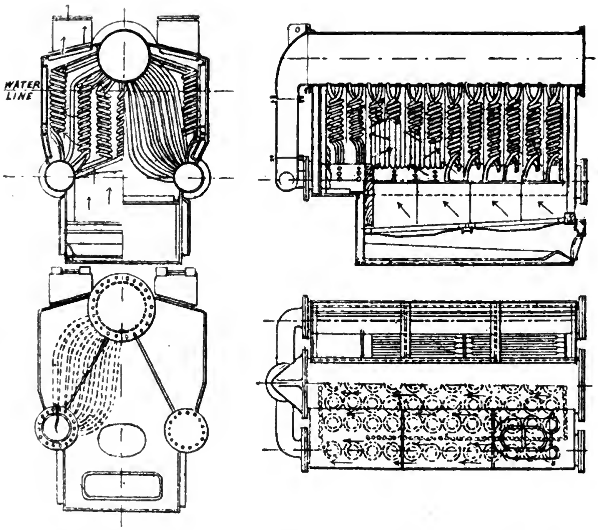


FIG. 251.

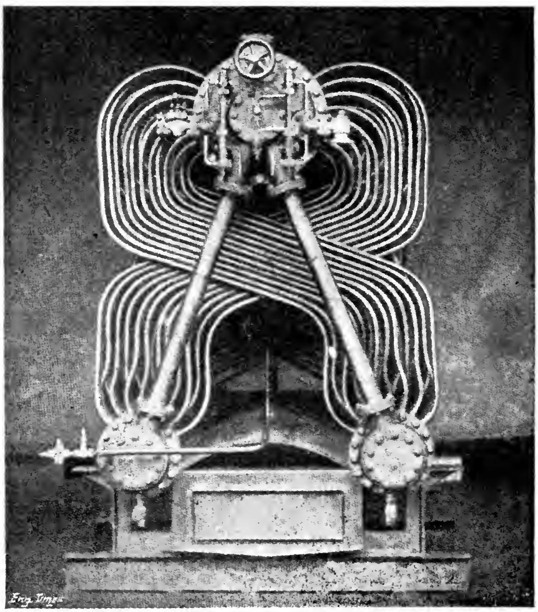


FIG. 252.

In addition to the nearly straight tubes connecting the two lower with the upper chambers, it had a number of tubes bent in cork-screw form filling up the combustion space, and thus adding considerably to the amount of heating surface.

Fig. 251 illustrates this boiler, which was described by Mr. J. T. Milton in Trans. Inst. N.A., Vol. xxxv., 1894, page 303.

Another form of the three-chamber boiler is made by the

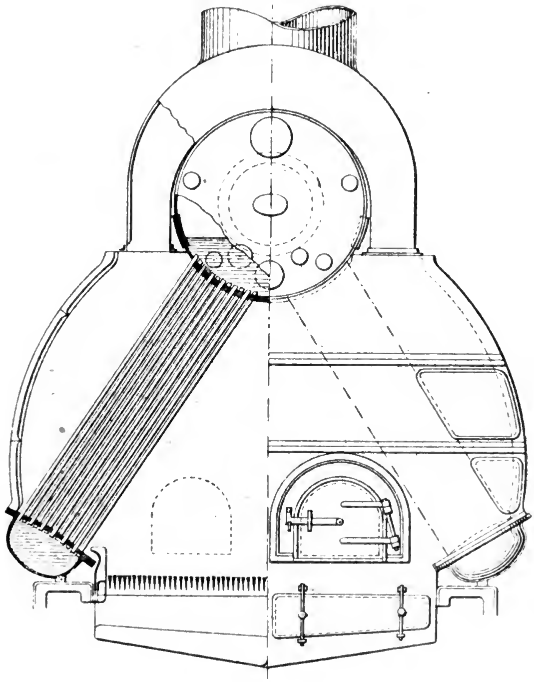


FIG. 253.

Liquid Fuel Engineering Co., of East Cowes, Isle of Wight, and is illustrated by Fig. 252. In this form the small tubes between the two lower and the upper chambers are crossed, as will be seen, and enter the steam chamber on the upper side.

Other three-chamber forms are those of H. A. House and R. Symon, 1893 (No. 17224); J. W. Davis, 1893 (No. 17473); G. F. Des Vignes, 1893 (No. 18419); B. H. Thwaite and J. B. Furneaux, 1893 (No. 20414); R. Schulz, 1894 (No. 1297); P. Smit

1894 (No. 7793); T. Herald, 1894 (No. 7794); Sir C. Ross, 1894 (No. 8472); O. D. Orvis, 1895 (No. 5740); J. Patterson and J. A. Sandilands, 1895 (No. 10441); P. Bentzene and C. F. Olsen, 1895 (No. 12754); E. Lagosse, 1895 (No. 16013); H. Du

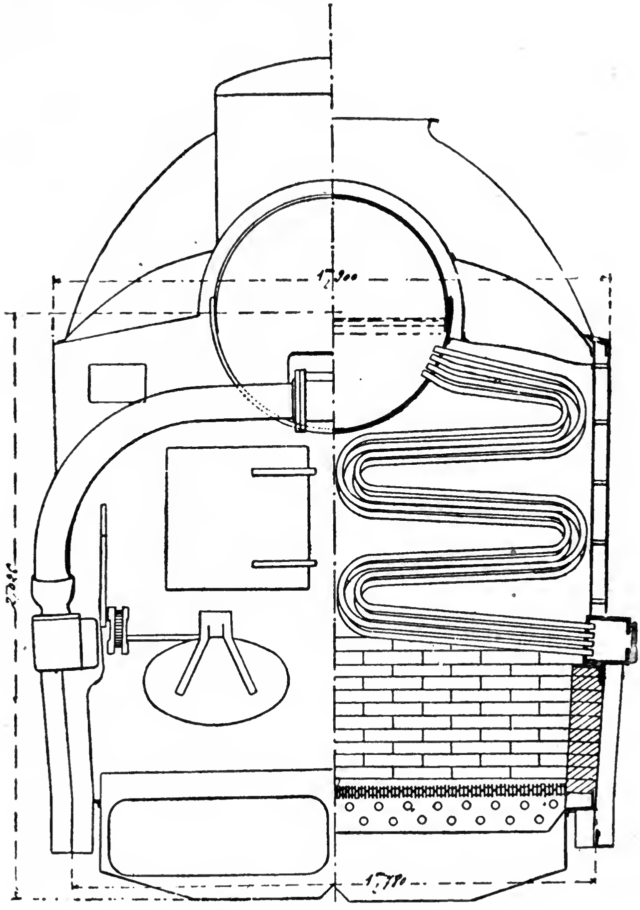


FIG. 254.

Temple, 1895 (No. 17200); H. McIntyre, 1896 (No. 4352); J. P. Hall, 1896 (No. 10774); Du Temple, 1897 (No. 11570); Hills and Young, 1897 (No. 19876), &c.

Yarrow's Boiler.—Mr. Yarrow's three-chamber boiler was patented in 1889 (No. 17958). In it the two lower chambers

are made of approximately semi-circular form, the flat surface enabling all the water-tubes to be inserted without a bend.

Fig. 253 illustrates this boiler, of which descriptions will be found in Trans. Inst. N.A., 1893, in *Cassier's Magazine* for August 1897, and in several other technical publications.

Du Temple Boiler.—The boiler of M. Du Temple, as now known and as patented in Britain in 1891 (No. 518), is another

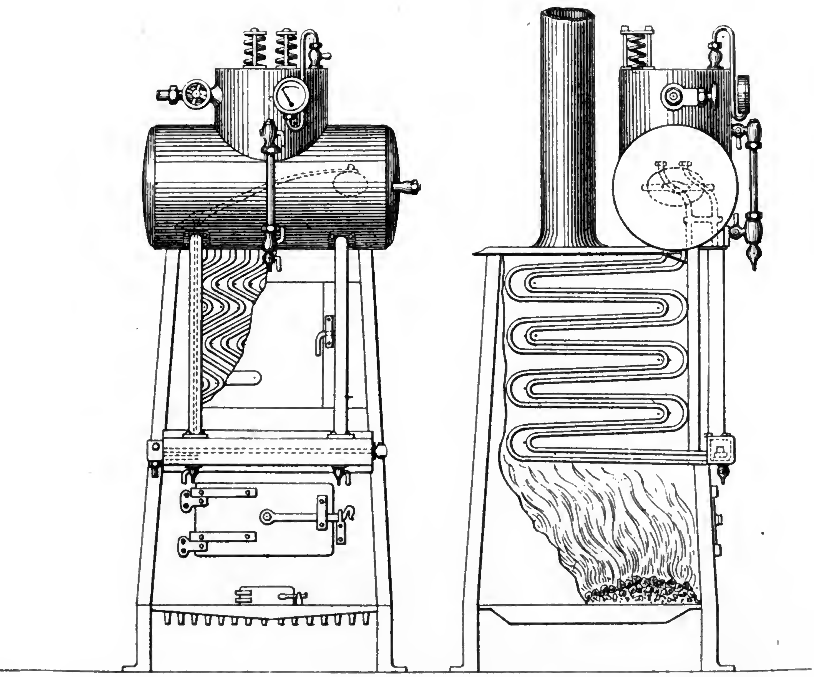


FIG. 255.

modification of the three-chamber design, the two lower chambers, however, being in this case of square shape, and the tubes having a more sinuous form than in most of the other modifications.

This boiler is illustrated in Fig. 254, but according to M. Bertin (" Marine Boilers," pp. 297-302), the tendency of recent improvement in this boiler has been towards a less sinuous form of water tubes and a greater approximation to the form

of the Normand boiler. This is shown in his British patent of 1895.

An older design, associated in this country with the name of M. Du Temple, is shown in Fig. 255, and is seen to combine the steam chamber at the upper ends of the bent water-tubes with a single water chamber of square shape at the lower ends. There is an external downcomer tube, as in the case of the other Du Temple boilers.

This form was patented in Britain in 1880 (No. 2554). Further patents are dated 1893 (Nos. 7923, 8251) and 1895 (No. 17200).

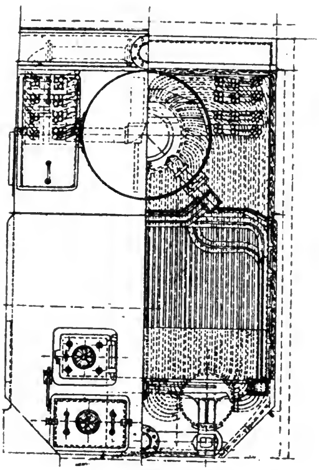


FIG. 256.

Cowles' Boiler.—The boiler of W. Cowles was introduced in America, and was patented in Britain in 1889 (No. 1161). It also adheres to the three-chamber type, but has a more elaborate arrangement of bent water-tubes than the other examples of this type. This will best be understood from the drawing. Fig. 256 represents this boiler as described by Mr. W. M. McFarland at the International Engineering Congress, Chicago, in 1893. It will be noticed that for a short length the back portion of the steam drum is reduced in diameter, at which part the water-tubes branch out from nearly the whole circumference. These tubes are made to fill the back space of the combustion chamber, the increased number of them enabling them to be laid fairly close together. Other tubes attached to box branches form the side walls of the combustion space.

Andrews' Boiler.—In 1892 (No. 13185) J. Andrews patented another example of the three-chamber type, which is shown in Fig. 257.

It differs from that of Yarrow and others in the form adopted for the chambers. The form of the upper chamber necessitates an additional steam drum.

Fleming and Ferguson's Boiler.—The boiler known as Fleming and Ferguson's "Clyde" boiler was patented by P. Ferguson and W. Fleming in 1892 (No. 24141). It is illustrated in Fig. 258, which shows that in this case the three chambers are connected by water-tubes, which are all bent throughout their entire

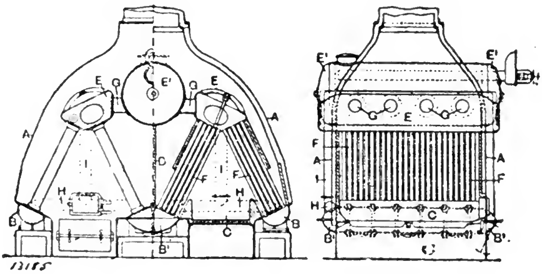


FIG. 257.

length to some arc of a circle. Otherwise there is no striking difference between this and other forms of the same type.

Normand Boiler.—This type was introduced in France by M. Normand, who first of all improved the Du Temple boiler, until it but slightly differentiates from some other forms, and later brought out the boiler which is associated with his own name.

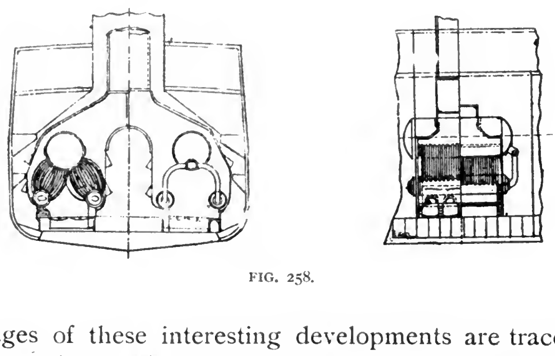


FIG. 258.

The stages of these interesting developments are traced in M. Bertin's work on Marine Boilers (Bertin and Robertson, pp. 297—313).

The Normand boiler is illustrated in Fig. 259, from which it will be seen that in the form of the water-tubes it resembles the

original Rowan three-chamber boiler more than any of the others. The Normand-Sigaudy boiler, 1895 (No. 4975) consists of two such boilers joined back to back.

The Normand boiler was patented in Britain in 1894 (Nos. 2315, 25004).

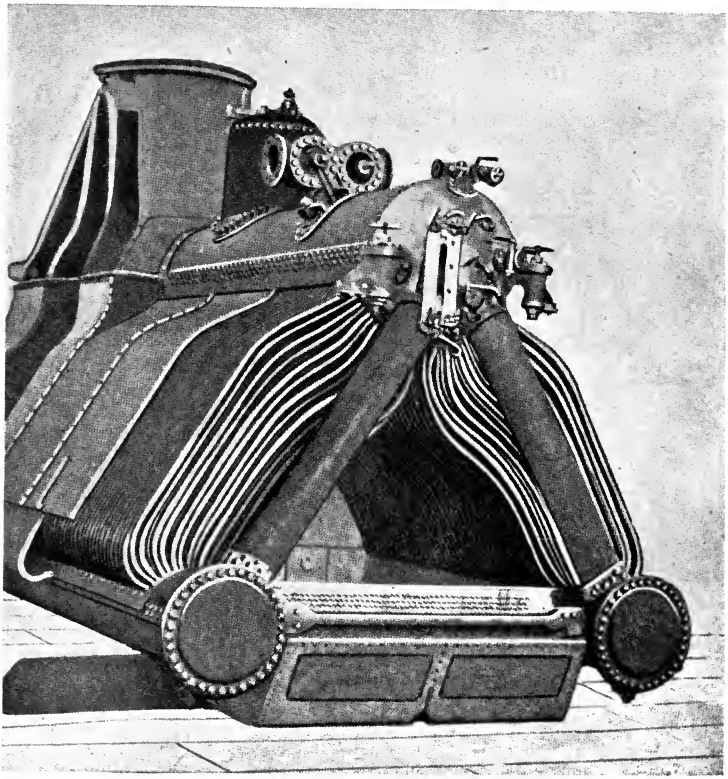


FIG. 259.

Blechynden Boiler. The late Mr. Blechynden patented in 1893 (Nos. 18311, 22949), 1895 (Nos. 9517, 17221) the form of three-chamber boiler with which his name is associated. It is shown in Fig. 260, and its peculiarity is seen to consist in having the steam chamber larger than usual, and a slight bend in the water-tubes so that any of these can be withdrawn or replaced

from hand holes arranged in the top of the steam chamber. Mr. Blechynden's boiler has, like several of the other modifications of this type, been introduced into the smaller vessels of H.M. Navy. It is now constructed by Messrs. Henry Watson and Sons, of Newcastle.

Reed's Boiler.—The only other marine boiler of this type, of importance, is the one introduced by Mr. J. W. Reed, in 1893 (Nos. 22982, 24124), 1896 (No. 4654), and constructed by Palmer's Shipbuilding Company.

It is illustrated in Fig. 261. In it the three chambers are all cylindrical in form, and the bend of the water-tubes resembles the form adopted in the Du Temple-Normand boilers of the "Mangini." The two rows of tubes over the fire are, however, in the Reed Boiler, zig-zagged to give increased heating surface, and down-comer tubes are supplied at each end of the horizontal chambers.

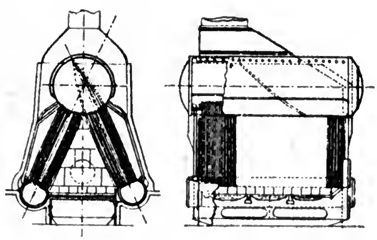


FIG. 260.

Maxim's Boiler.—The variations in form of water-tubes adopted in this type is further illustrated in the boiler constructed by Mr. H. S. Maxim for his flying-machine. This is shown in Fig. 262.

Mumford's Boiler.—A modification of this type was introduced by Mr. A. G. Mumford of Colchester, in 1893, for small boilers, from which he developed another arrangement suitable for larger powers. In this case, as is shown in Fig. 263, the three chambers are attached by branch pipes to boxes which contain clusters of small bent water-tubes. The intermediate joints give undoubted facility for the removal and repair of any of the individual clusters, and in the erection of a boiler on board ship there is no riveting or tube expanding required. This constitutes the special advantage possessed by this design. Mr. Mumford's patents are dated, 1893 (No. 8729), 1895 (Nos. 8043 and 15549), 1897 (No. 8498), 1898 (No. 19008), 1899 (No. 9898).

This boiler has also been introduced for trial in H.M. Navy.

Another modification of the three-chamber design was

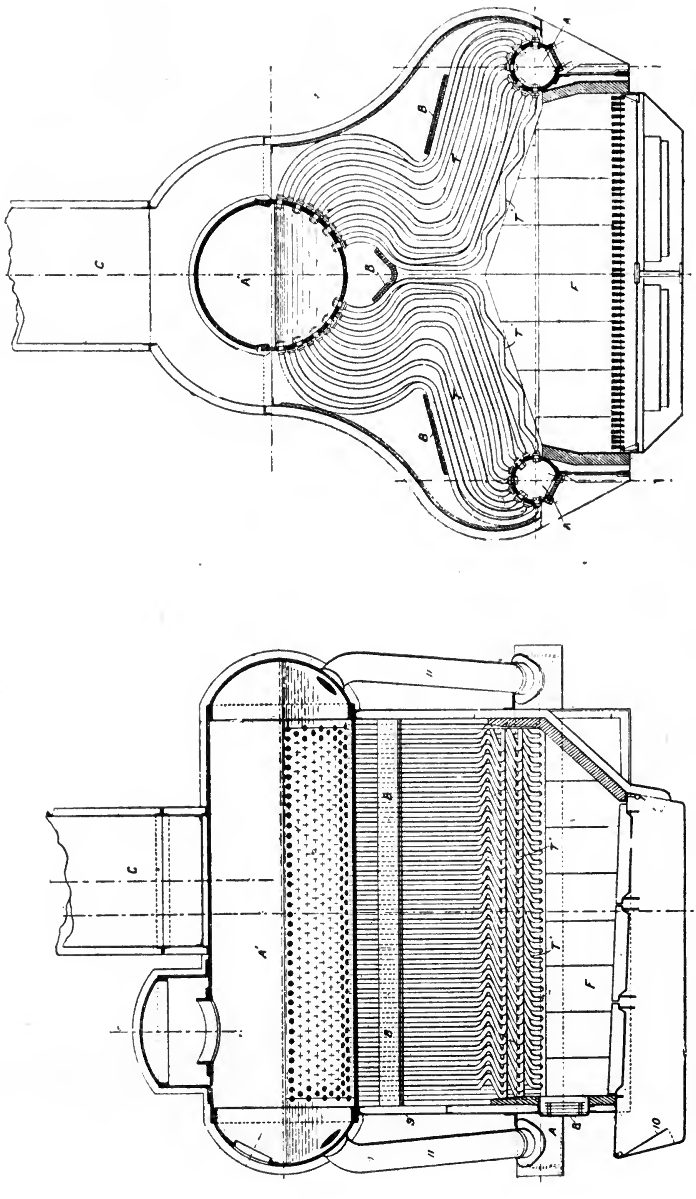


FIG. 261.

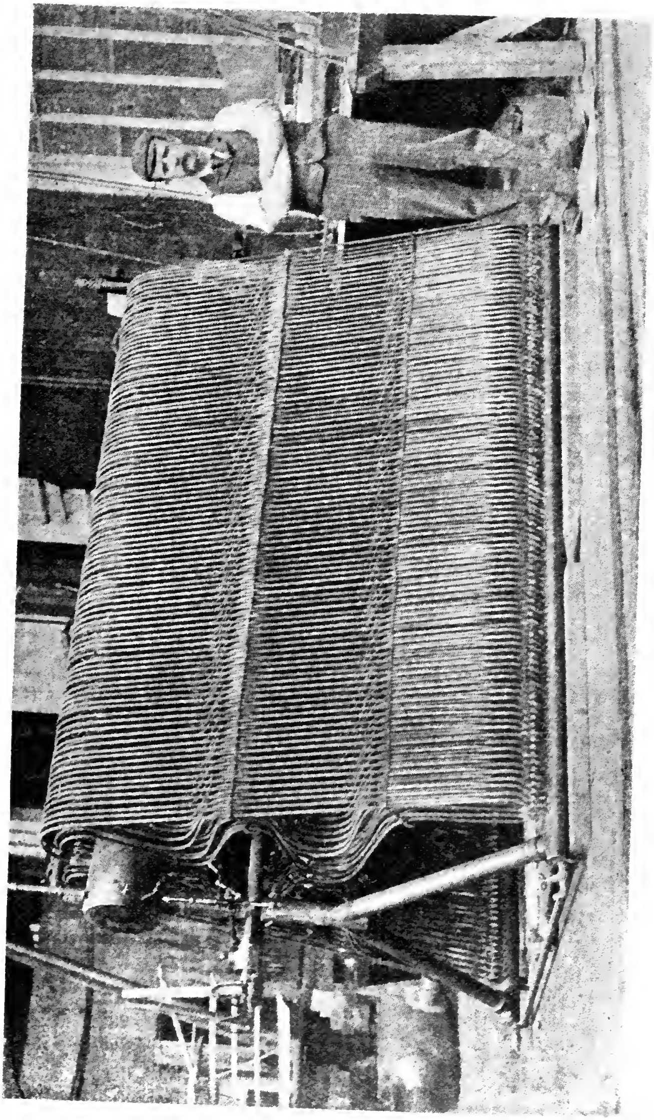


FIG. 262.

proposed by C. S. Galloway in 1894 (No. 19913), and a further one by Mr. James Weir later.

Weir Boiler.—Mr. Weir patented in 1894 (No. 3724) a boiler with two horizontal drums connected by a number of small water-tubes; also a central vertical chamber and small tubes curving from the top to near the bottom, and other forms. In subsequent patents, No. 4995 and 28961 (1896), No. 9177 (1897) and No. 12308 (1898), he developed various designs with the object of forming, by means of bent water-tubes, a combustion space for secondary combustion of the hot gases which are cooled often

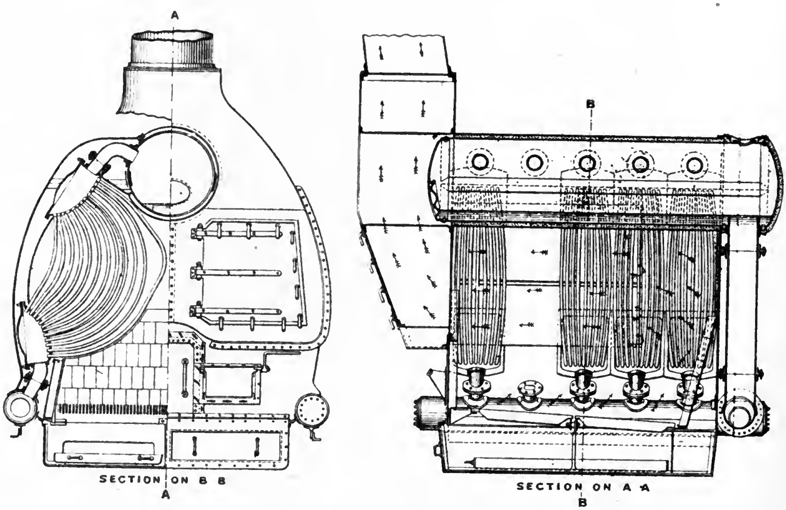


FIG. 263.

to the point of extinguishing flame by their first contact with the heating surface. As shown by his paper, read before the Institute of Engineers and Shipbuilders in Scotland, Vol. xlii. pp. 12—40 and plate 2, Mr. Weir finally fixed upon the three-chamber form as the most suitable for carrying out his plan.

With regard to all the forms of this three-chamber type, it is apparent that the more the water-tubes are bent or twisted into fantastic shapes, the more is the advantage of having straight vertical tubes lost, and facility of examination is also lost in proportion.[1]

[1] See *The Engineer.* November 21, 1890, p. 408.

Mosher's Boiler.—The boiler of C. D. Mosher, introduced in America in 1880, but patented in Britain in 1892 (No. 1725), has only two chambers to each group of tubes, but usually four chambers are connected to form a boiler as is shown in Fig. 264. The arrangement of the water-tubes is in some respects similar to that of the Cowles boiler, but in delivering their contents above the water-line in the top chamber, it resembles the

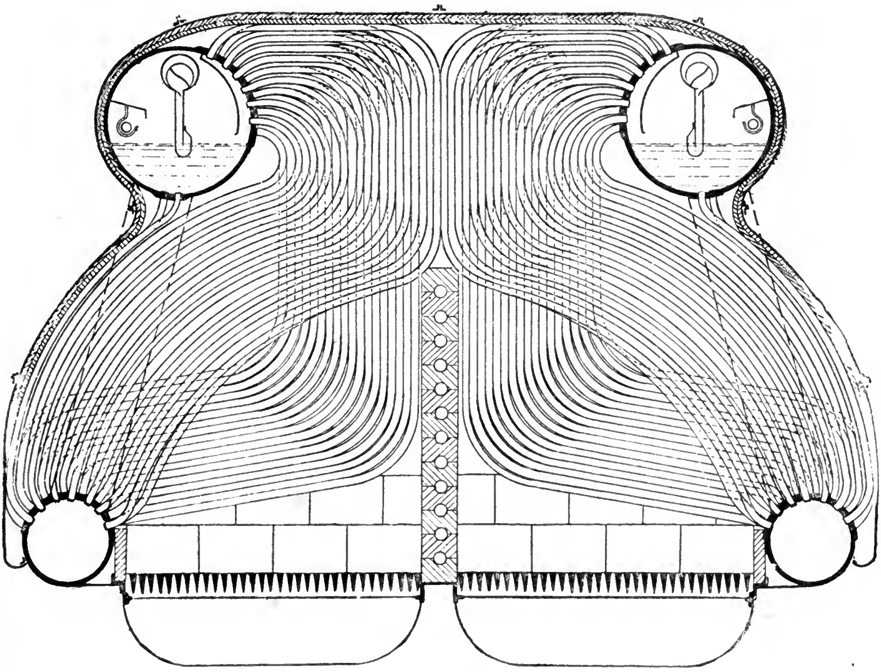


FIG. 264.

Thornycroft boilers. Further designs were patented by Mosher in 1894 (Nos. 17285 and 17286).

Seabury, Symon-House, and Gurney Boilers.—Seabury's Boiler of 1892 (American patent No. 497432) has also two chambers, but the water-tubes are bent outwards on each side to embrace the fire, which is placed between the two horizontal chambers—see Fig. 265.

Of a similar design is the Symon-House boiler (illustrated in

Bertin and Robertson's Marine Boilers, page 324), which is almost the counterpart of the boiler patented by L. Mills and W. Clark in 1878 (No. 3865), whilst both of these boilers recall the original boiler of Goldsworthy Gurney in 1825 (No. 5270), which is illustrated in Fig. 266, and Craddock's Boiler of 1857 (Nos. 931 and 1162).

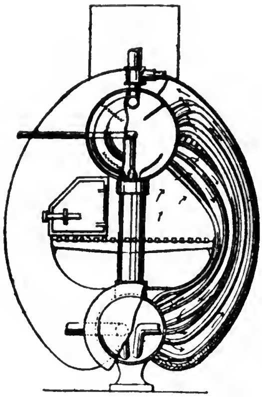


FIG. 265.

A number of Patents for vertical or vertically inclined water-tube boilers were taken out during the years from 1880 to 1896, few of which require any particular notice. Of these the names of the following are sufficient :—Ballian, 1880 (No. 4662), Stevenson, 1883 (No. 5907), Lake, 1884 (No. 1420), Leutner, 1884 (No. 12013), Allen, 1886 (No. 10780), Seabury, 1889 (No. 4279), Haurez, 1889 (No. 10056), King and Clark, 1889 (No. 11735), Van Steenbergh, 1890 (No. 3020), Drory, 1892 (No. 15069), W. H. Watkinson, 1896 (No. 15721) (see page 506).

Ward's Boiler.—In 1888 (No. 11617), Mr. Chas. Ward of Charlestown, U.S.A., patented in Britain a boiler composed

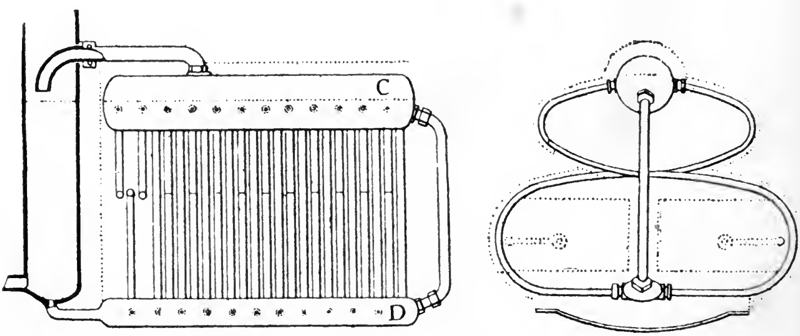


FIG. 266.

principally of vertical water-tubes, which he had introduced in America. This is illustrated in Fig. 267, and is usually known as Ward's Torpedo-boat Boiler. This boiler is circular on plan,

the casing being cylindrical. At the bottom, and supported by the ash-pit, is a cast steel circular tube of about $4\frac{1}{2}$ inches diameter, forming a circle of some three feet. Small branches or seats are formed on the top side of this ring into which vertical water-tubes are fitted to form two rows, placed zigzag on plan, surrounding the fire. At the top these tubes are bent to a quarter of a circle to enter radially the shell of a vertical cylindrical steam drum. From the bottom of this steam drum three rows of pendant tubes are fixed, so that they hang slightly inclined towards the vertical tubes outside. The lower ends of these hanging tubes are closed by caps, and each tube has an internal tube for water circulation. The enclosing casing is of sheet iron, double, with asbestos board between the two sheets.

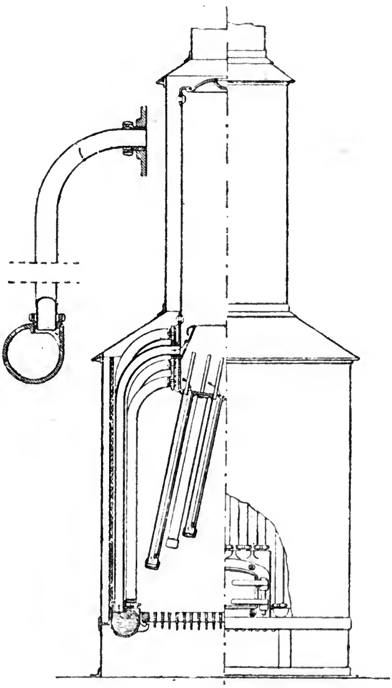


FIG. 267.

Stirling's Boiler. — The boiler known as the Stirling Water-tube Boiler was patented in this country by A. Stirling in 1889 (No. 11413), further patents being taken out in 1892 (No. 13614) and 1895 (No. 13733). It is represented in Fig. 268, and is composed of vertically inclined water-tubes set radially into horizontal chambers at each end in the same manner as in the Rowan and Horton boiler of 1869.

The Stirling boiler was introduced in America and has been used hitherto only for land or stationary purposes.

Similar designs have been patented in this country by J. Pierpoint in 1892 (No. 7039), and in America by H. S. Pell on 22nd December, 1893.

Particulars of the Stirling water-tube boilers used at the Chicago Exhibition, will be found in *The Engineer*, of August 4th, 1893, p. 110. As now made by the Stirling Boiler Co., Ltd.,

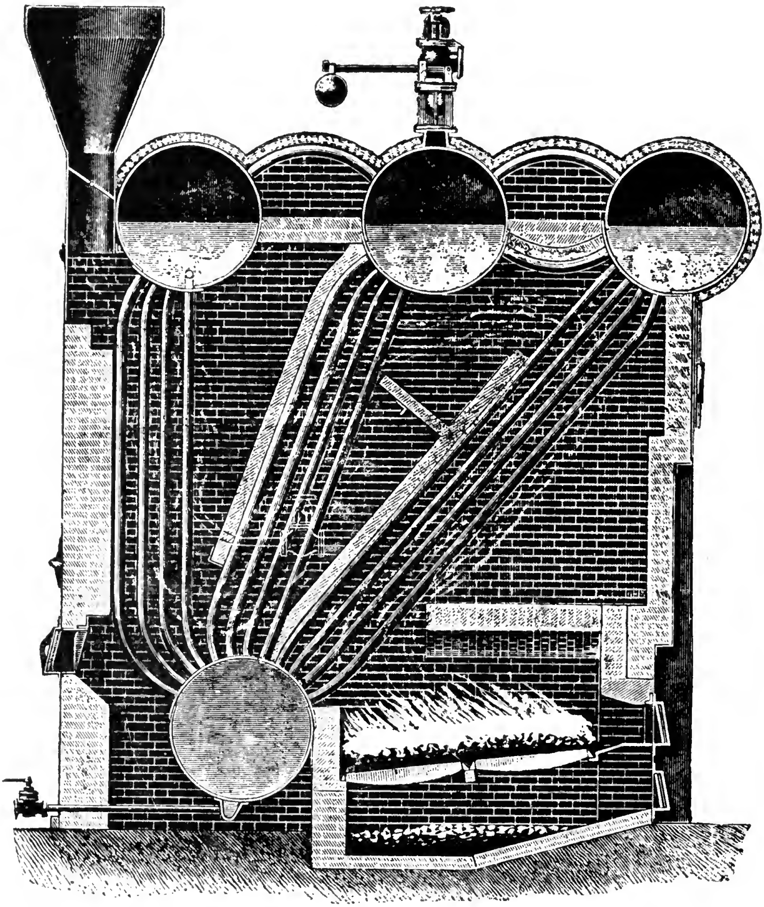


FIG. 268.

of Edinburgh and Motherwell, this boiler as adapted for use on land has been modifieed. Particulars of its latest form will be found in *The Engineering Times*' Record of the Machinery in the Glasgow International Exhibition, in *Feilden's Magazine*

for 1901 and elsewhere. See Fig. 269. A marine boiler projected by this Company is in course of development also.

Jardine's Boiler.—A boiler on somewhat similar lines was patented by John Jardine in 1896 (No. 5702), and is known as the "Glasgow Patent Water-tube Boiler."

In this boiler the vertical water-tubes are connected with two water drums behind the furnace, in the same way as in the

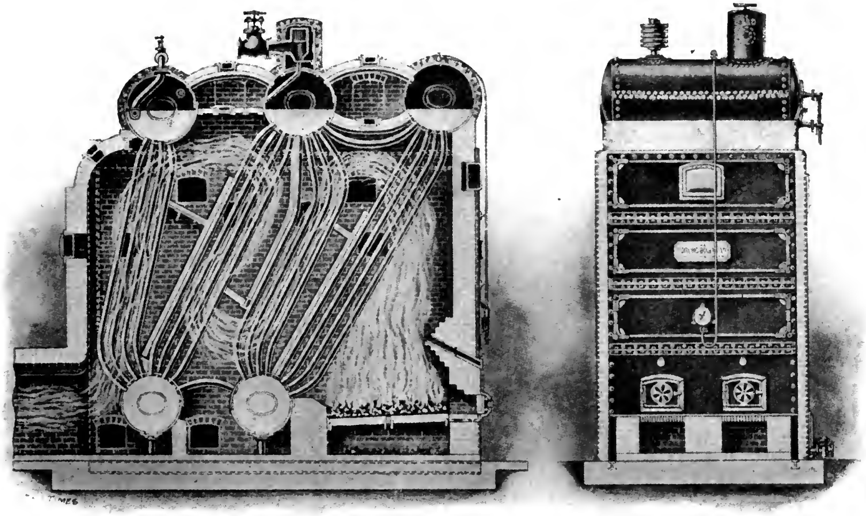


FIG. 269.

Stirling boiler, but, instead of its three steam drums above placed parallel with the water drum, in the "Glasgow" boiler there are two horizontal steam drums placed at right angles to the axis of the water drums below.

Fig. 270 illustrates this boiler, which is manufactured by Messrs. Duncan Stewart and Co., Ltd., of Glasgow.

Peterson's Boiler.—The Peterson-Macdonald boiler is allied to the three chamber type, but has some distinctive features. The vertically-inclined tubes are connected in groups or "nests" of

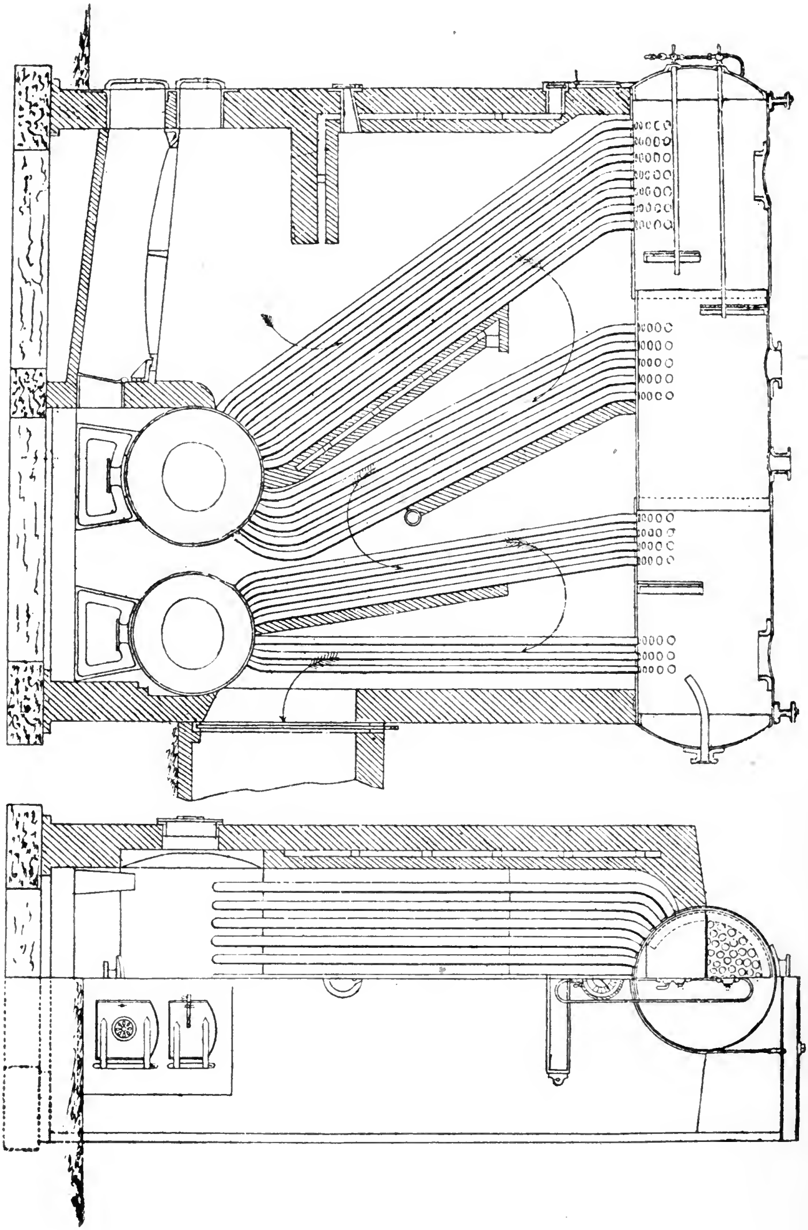


FIG. 270.

nine tubes to a steel box at each end, and these boxes are connected to the steam drum at the top end of the tubes, and to branches from stand pipes at the other end. These stand pipes

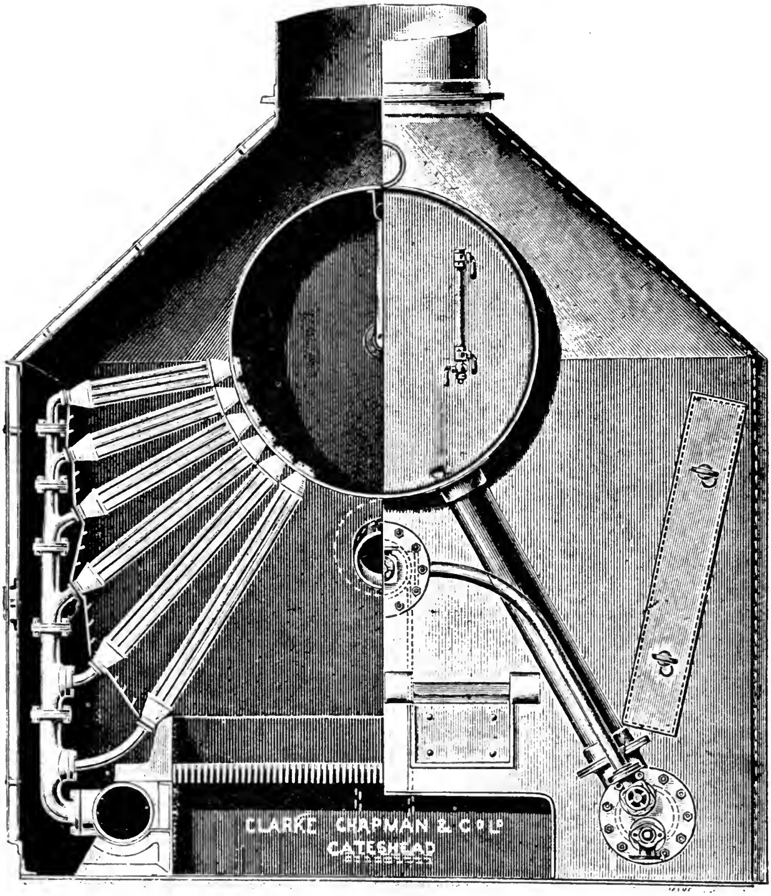


FIG. 271.

connect at each side of the fire-place to small water drums placed alongside the ashpit.

Fig. 271 shows this boiler as so arranged.

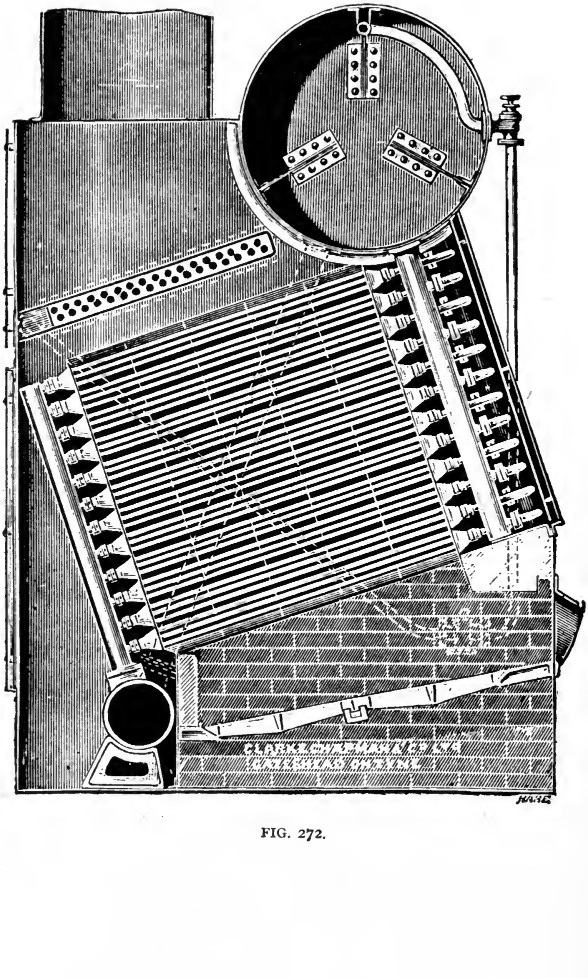
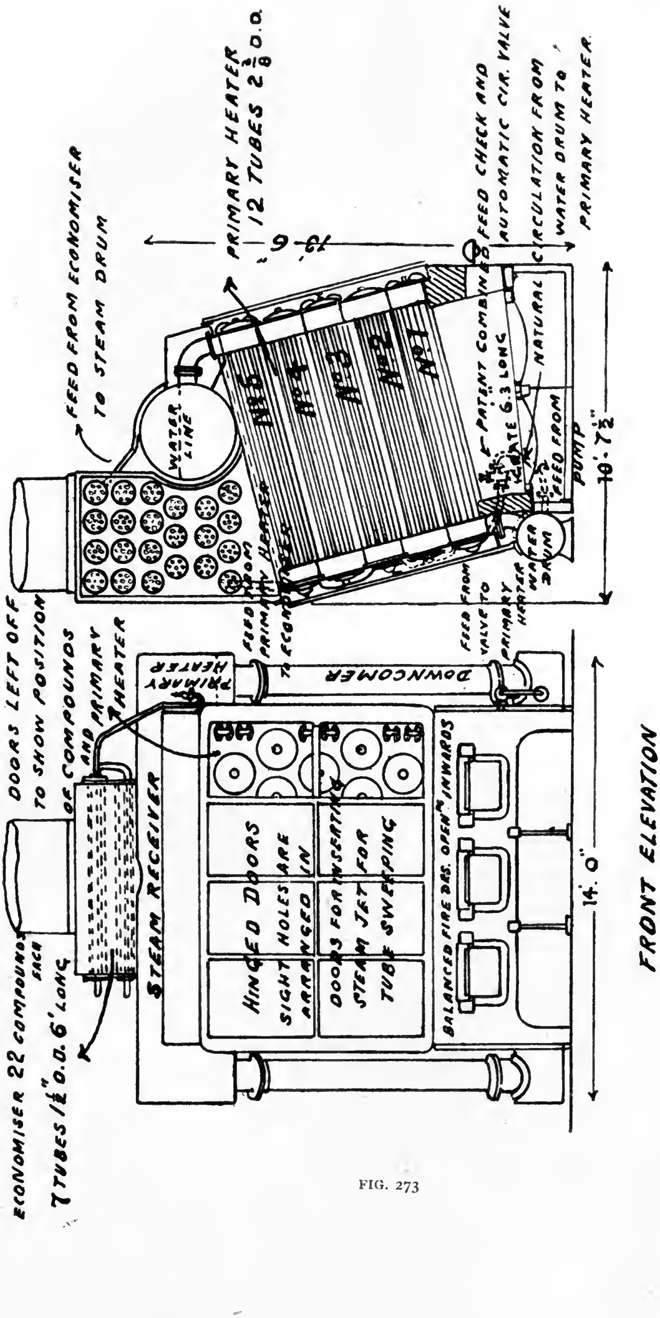


FIG. 272.



FEED FROM ECONOMISER TO STEAM DRUM
PRIMARY HEATER 12 TUBES 2 1/8" O.D.
19'-6"
FEED CHECK AND AUTOMATIC CIR. VALVE
NATURAL CIRCULATION FROM WATER DRUM TO PRIMARY HEATER
PATENT COMBINED
GRATE 6.3 LONG
FEED FROM PUMP
10'-7 1/2"
WATER LINE
No 5
No 4
No 3
No 2
No 1
WATER DRUM
FEED FROM VALVE TO PRIMARY HEATER
FEED FROM PRIMARY HEATER TO ECONOMISER
DOORS LEFT OFF TO SHOW POSITIONS OF COMPOUNDS AND PRIMARY HEATER
PRIMARY HEATER
DOWNCOMER
STEAM RECEIVER
HINGED DOORS
SIGHT HOLES ARE ARRANGED IN
DOORS FOR INSERTING STEAM JET FOR TUBE SWEEPING
BALANCED FIRE DRS. OPEN'G INWARDS
14'-0"
FRONT ELEVATION
ECONOMISER 22 COMPOUNDS EACH
7 TUBES 1 1/2" O.D. 6' LONG

FIG. 273

Another form arranged as a horizontally inclined boiler is shown in G. Halliday's book on "Steam Boilers," p. 334, from which Fig. 272 is taken.

Experience in the manufacture of this boiler as originally designed is said to have shown that some alteration was desirable in consequence of difficulty in readily altering the angles of the tubes for any small variation of width of fire-grate. Accordingly, the horizontal form was proposed and a later improvement upon that, which has been developed by Messrs. Clarke, Chapman and Co., Ltd., and adopted by the Peterson Water-tube Boiler Co., is shown in Fig. 273.

In addition to a new arrangement of the nests of tubes, or of the "compound tubes," as they are called, an economiser and a primary heater, which latter consists of a serpentine coil of tube of $2\frac{3}{8}$ ins. outside diameter, arranged on the two wings of the boiler, are added. Feed regulating valves are also used, so that the water may be made to traverse the heater until natural circulation commences. The water, heated first in the primary heater and then in the economiser, is delivered into the steam drum.

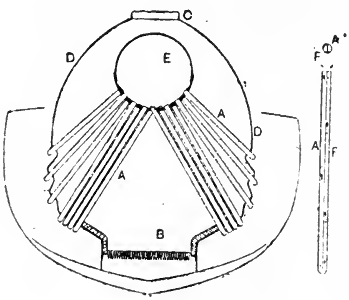


FIG. 274.

The patents for the Peterson boiler are dated, 1891 (No. 18698), 1893 (No. 23577), 1894 (No. 23346), 1895 (No. 17722), and the improved form 1899 (No. 12343).

Stevenson's Boiler.—G. Stevenson, in 1883 (No. 5907), patented an arrangement of vertical and vertically inclined water-tubes fastened to the outside of a cylindrical water chamber. The tubes were closed at the end and each contained a circulating tube.

Yarrow's Boiler.—A more workable design having some ideas in common with Stevenson's, was patented by A. F. Yarrow in 1893 (No. 24690). This consisted of a cylindrical water and steam drum, from which a number of water tubes depended obliquely, so as to spread on each side of the fire, see Fig. 274.

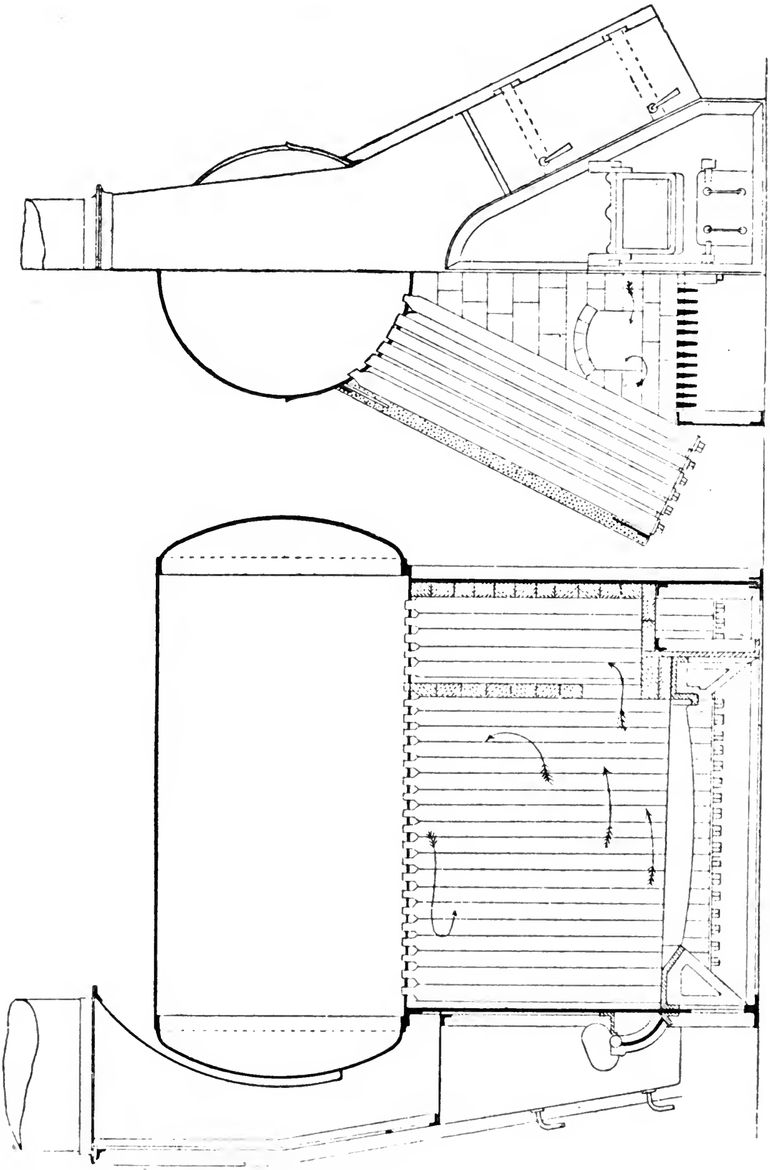


FIG. 275.

These tubes were closed at their lower end, and each contained a circulating tube or partition.

Thom's Boiler.—Considerable improvement in this design was made by John Thom in his patent of 1896 (No. 2793). This boiler is illustrated in Figs. 275 and 276, from which it will be seen that although it has, like Yarrow's, tubes, closed at one end, depending obliquely from a cylindrical steam and water chamber, yet by the ingenious plan of reducing the diameter of some of these

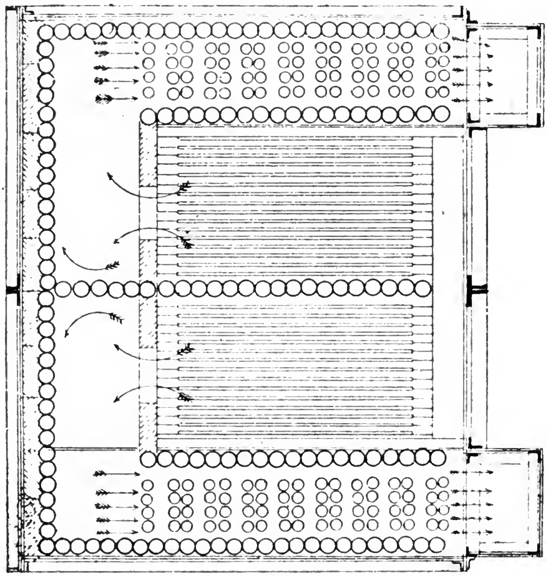


FIG. 276.

tubes where they enter the tube plate, Mr. Thom was enabled to arrange them in contact to form water walls, dividing the furnace space for two fires and constructing combustion chambers and flues, almost at will. This boiler has been successfully introduced by Mr. Thom, for use in both marine and land work.

Phillips' Boiler.—Another boiler of the same class has been proposed by H. F. Phillips.

The earlier form of this boiler, which does not seem to have been patented, is shown in Fig. 277, from G. Halliday's "Steam Boilers" (pp. 336, 337). In this form, the tubes were spread out

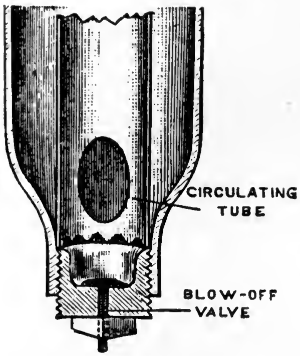


FIG. 277A.

to form five rows of equal length, on each side of a single fire-place. The outer tubes were contracted at their lower ends to receive a plug containing a small blow-off valve, and the inner tubes rested on the plug and had holes cut in their sides and on the bottom edge to permit of water circulation (Fig. 277A). In the later form of the Phillips' boiler, shown in Fig. 278, which was patented in 1898 (No. 8814), the pendent tubes are arranged to form spaces for five fire-places with a double row of tubes between each of them, and on the two outside flanks of the boiler, seven rows of tubes. The idea

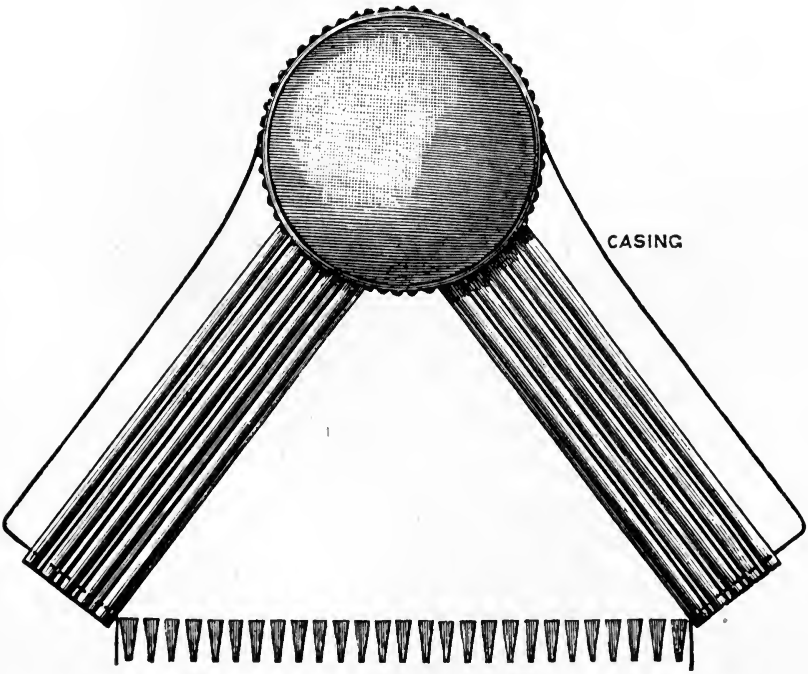


FIG. 277.

of this arrangement is to have as large a proportion of the heating surface as possible under the influence of the radiant heat of the fires. There is, of course, perfect freedom of expansion and contraction in the tubes of this class of boiler, so that it avoids many strains in working. This form of the Phillips boiler is stated to have performed well on test, although

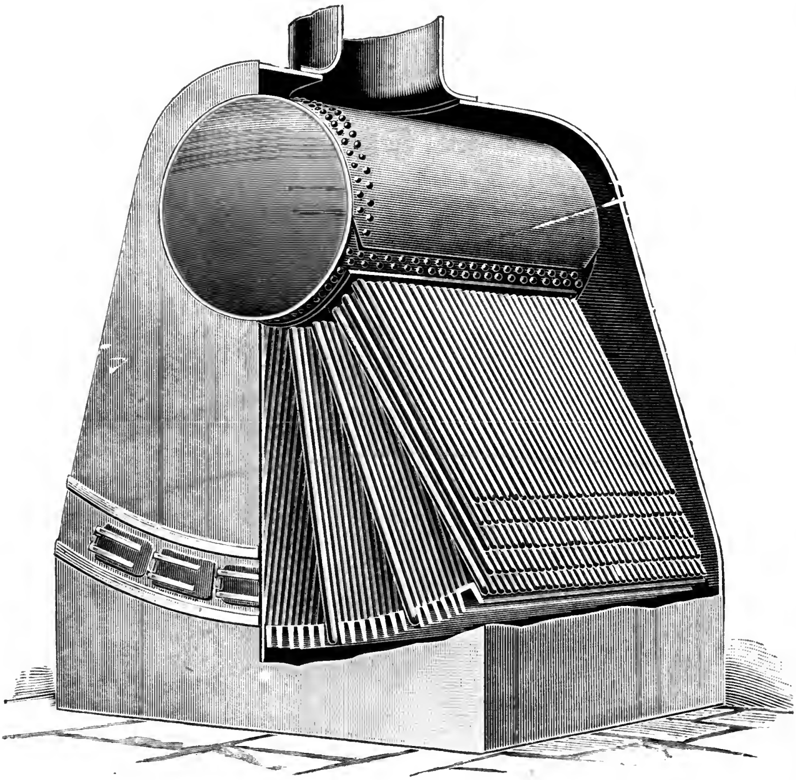


FIG. 278.

the rate of evaporation per square foot of heating surface was 8·15 lbs. of water at 250 lbs. per square inch pressure of steam, and 8·1 lbs. water per lb. of coal from and at 212° F., which cannot be called a high rate for a water-tube boiler.

Haythorn Boiler.—The Haythorn boiler was patented in 1894 (Nos. 9570 and 12846). In it the water-tubes are vertical

at starting from the lowest point, and, after following an easy curve, finish off at an incline above the horizontal. The tubes are connected to headers at each end; the lower headers being laid side by side behind the fire-grate, in the line of fire bars, and the upper headers at the boiler front inside

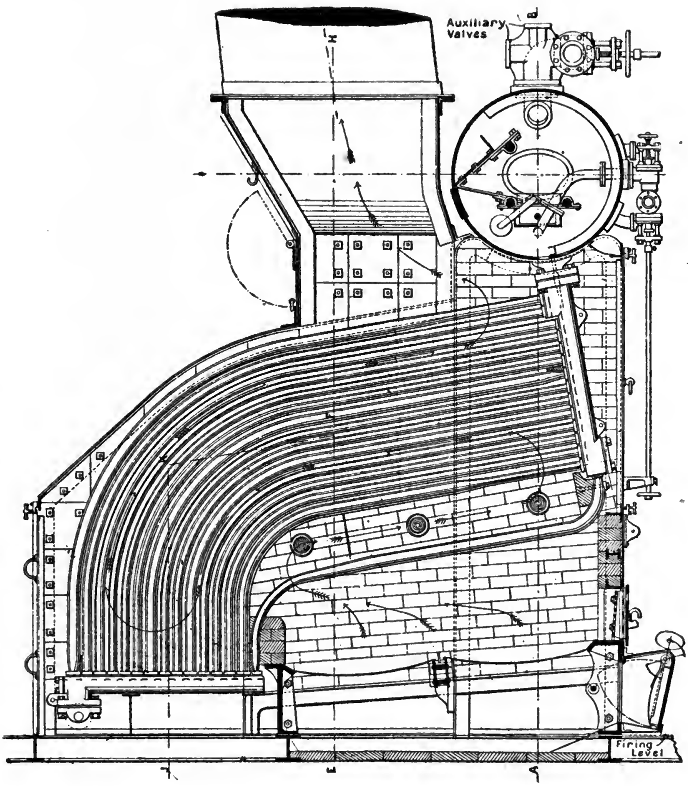


FIG. 279.

the casing. Each pair of headers (the upper and lower) provides for a double row of water-tubes, and either one or two larger tubes which are on the outside of all and act as downcomers. The portion of the front headers to which the downcomer tubes are attached is enlarged to form a separate passage for the water, the upward steam passage being in

front. A cylindrical drum is placed across the boiler front, and is connected by flanges to the tops of the front headers. As first made, the Haythorn boiler was as illustrated in *Engineering*, Vol. lx., page 680, whilst in Fig. 279 the latest form is shown as arranged for marine use. The water level is at about the centre of the cylindrical drum, into which the feed is delivered, whilst a door for clearing out mud and a blow-off cock are provided at the lowest point of the back headers below the downcomers. Formerly fire bricks were used as baffle plates, but in the recent form these are abolished, and the tubes are laid together where wanted to form water walls.

The boilers patented by Galloway and Wilson, 1861 (No. 1948), William Inglis, 1862 (No. 3307), and J. T. Romminger, 1865 (No. 771) may be classed with vertical water-tube boilers, as also the designs patented by the author in 1894 (No. 8170). Of modifications of the vertical design the one proposed by Shepherd in 1873 (No. 1849), and 1877 (No. 1699) is, perhaps, the only one requiring notice.

Shepherd's Boiler.—This boiler is illustrated by Fig. 280, and was composed of vertical vessels, partly cylindrical and partly conical in shape, set in two or three rows, with horizontal cylinders or large tubes below, into which the feed entered. A certain portion of the cylindrical upper part of the vertical vessels was used as steam space, and a steam pipe connected all these vessels by vertical branches from their domed tops at the centre.

Coil Boilers.—At an early date various forms of coiled tube boilers were proposed, probably because a considerable area of heating surface, without the trouble of making many joints, could be obtained within a small space. Fitch and Voight and James Rumsey were the first to bring forward this design, and they were soon followed by Seaward and Paul, who used forms of coils in the construction of their "flash" boilers. (See pp. 361—362 ante).

Gurney's Boiler.—Goldsworthy Gurney in 1825 (No. 5270) and in 1827 (No. 5554) patented two forms of water-tube boilers, the first having been the one already referred to (p. 458), whilst the second was more properly a coil boiler. It has been represented by Fig. 281, which was the form

ultimately adopted for this boiler in connection with the historic

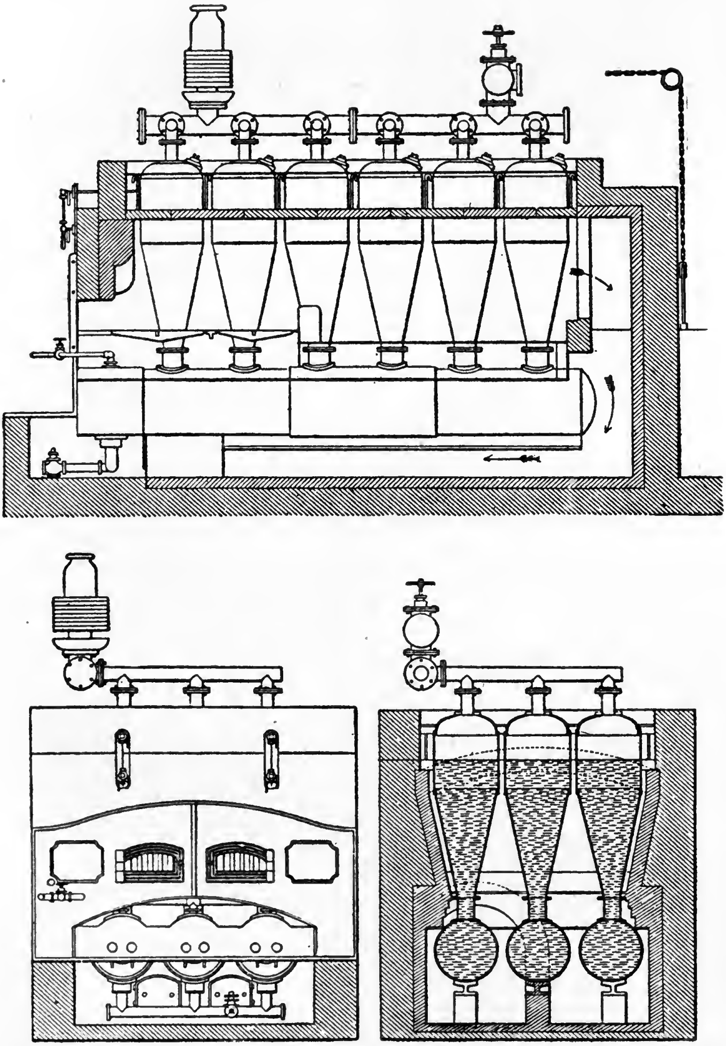


FIG. 280.

introduction of steam automobilism in the early part of the 19th century. An earlier form of this boiler is shown in

Fig. 282, which is evidently less suitable for the confined space of a motor vehicle.

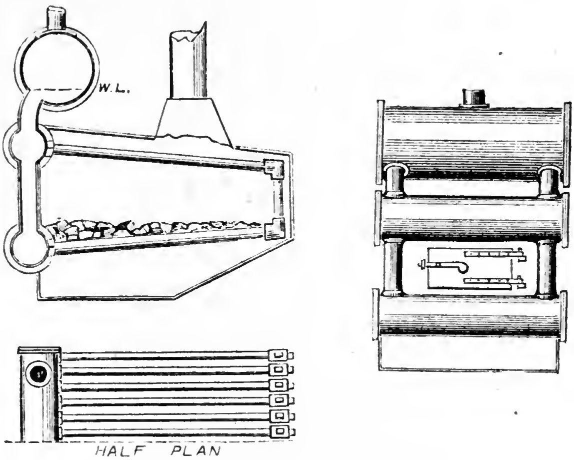


FIG. 281.

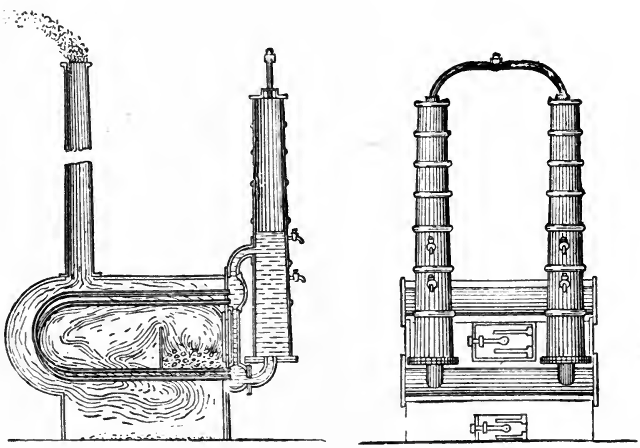


FIG. 282.

J. Rawe and J. Boase followed in 1830 (No. 5956) with a boiler composed of a series of helical coils of tubes, but of its use we have no record.

Dance and Field's Boiler.—The boiler of Dance and Field, 1833 (No. 6465), was, however, introduced in motor-car work, and seems to have done its work fairly well. It is shown in Fig. 283 as constructed by Messrs. Maudslay and Field for

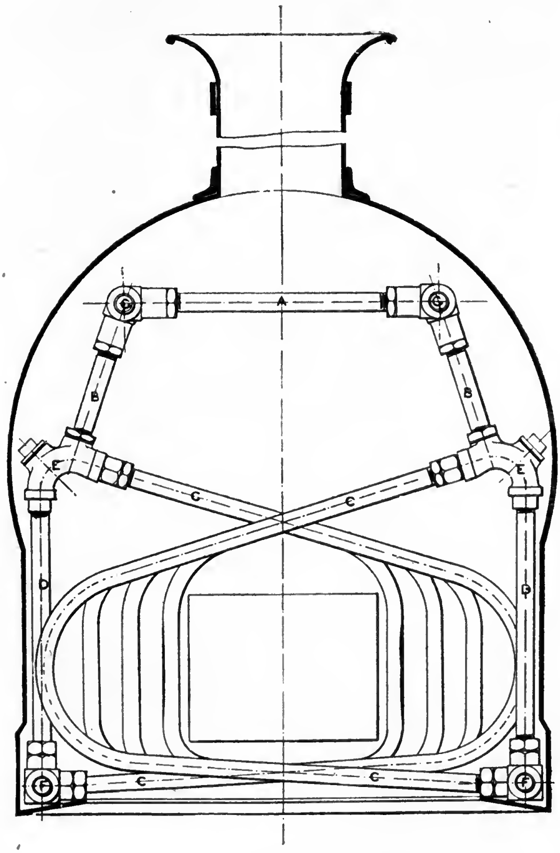


FIG. 283.

the steam motor which ran from London to Reading and back, towing an omnibus full of passengers.

One of W. H. James' patents, viz., the one for 1855 (No. 1998) was for a coiled tube boiler, but excepting the Belleville designs of 1852 and 1856 (already mentioned)

there was no coil boiler of importance brought out for many years. The following are the principal patents for coil boilers :—W. Morgan, 1838 (No. 7848), J. T. Beale, 1840 (No. 8564), Belleville, 1852 and 1856, W. E. Newton, 1854 (No. 1361), J. H. Johnson, 1855 (No. 223), M. F. Isoard, 1855 (No. 1637), J. A. Hopkinson, 1858 (No. 2558), G. Scott, 1858 (No. 565) and 1859 (No. 2317), S. S. Bateson, 1860 (No. 480).

Matheson's Boiler.—Some of these inventors make use of spiral coils, but the most simple application of this device is found in the boiler patented by H. Matheson in 1861 (No. 94), which is represented in Fig. 284, as illustrated by Mr. Thornycroft in Min. Pro. Inst., C.E. Vol. xcix. Plate 1. Fig. 7. Although this boiler apparently provides for continuous and systematic circulation of the water in one direction, the danger of this and of all similar arrangements is that a rapid generation of steam in the water supply pipe to the coil (or the lowest branch of the coil), which is exposed to the direct heat of the fire, would probably cause an interruption of the circulation on account of that steam seeking the readiest means of escape, some of it preferring to go up through the water chamber rather than by the longer and more tortuous road provided by the spiral. Such action has happened in several water-tube boilers of different designs, and the immediate overheating of the tubes or chambers has made the re-entry of water all the more difficult, so that damage has nearly always resulted. (See, for example, Griffiths' boiler, p. 374 ante.)

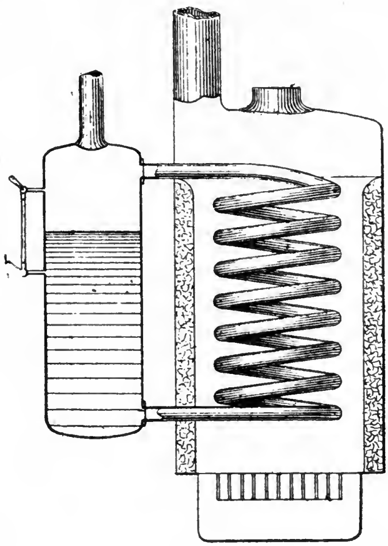


FIG. 284.

John Elder's Boiler.—This action was evidently anticipated in such a boiler by the late John Elder, whose patent of

1862 (No. 1214), for a practically similar design to that of Matheson, provides for the introduction in the upper branch from the coil of a revolving screw to propel the water downwards through the coil. This arrangement is shown diagrammatically in Fig. 285, which is taken from Mr. G. Halliday's "Steam Boilers."

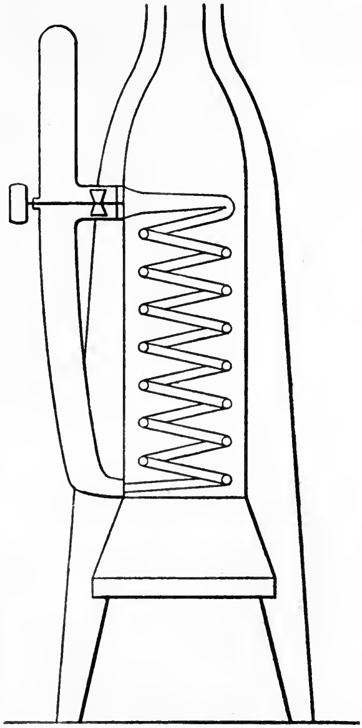


FIG. 285.

The patents of H. Chamberlain, 1863 (No. 38), G. T. Bousfield, 1866 (No. 1913), P. J. Ravel, 1868 (No. 3479), C. Tyson, 1877 (No. 4811), E. T. Hughes, 1877 (No. 4881), D. Clerk, 1879 (No. 2423), and W. H. Northcott, 1880 (No. 3176), call for no special description.

Ward's Boiler.—C. Ward's patent of 1879 (No. 4074) was for the coil boiler, which he commenced to introduce into marine practice in America in 1877. This boiler is composed of a central vertical drum or cylindrical chamber, which has a horizontal branch at two-thirds of its height, and branch pipes connecting with two horizontal cylindrical chests or branches on the floor line. From these lower branches vertical stand pipes or "water-legs" rise, those under the upper branch connecting directly with it, whilst those on the other side of the central chamber have their top ends closed by plugs. From each side of these stand pipes semi-circular "coils" of tubes proceed, so as to form a number of concentric circles around the central chamber. These circular water-tubes are laid at a slight angle from the horizontal, so that the flow of steam will be towards the stand pipes, which are connected with the top branch to the central drum. The feed water is delivered

into the central drum, in which it descends to the bottom branches and ascends by the vertical stand pipes, thus supplying the "coils." Figs. 286 and 287 show this boiler, which was fully described by Mr. Ward at the International Engineering

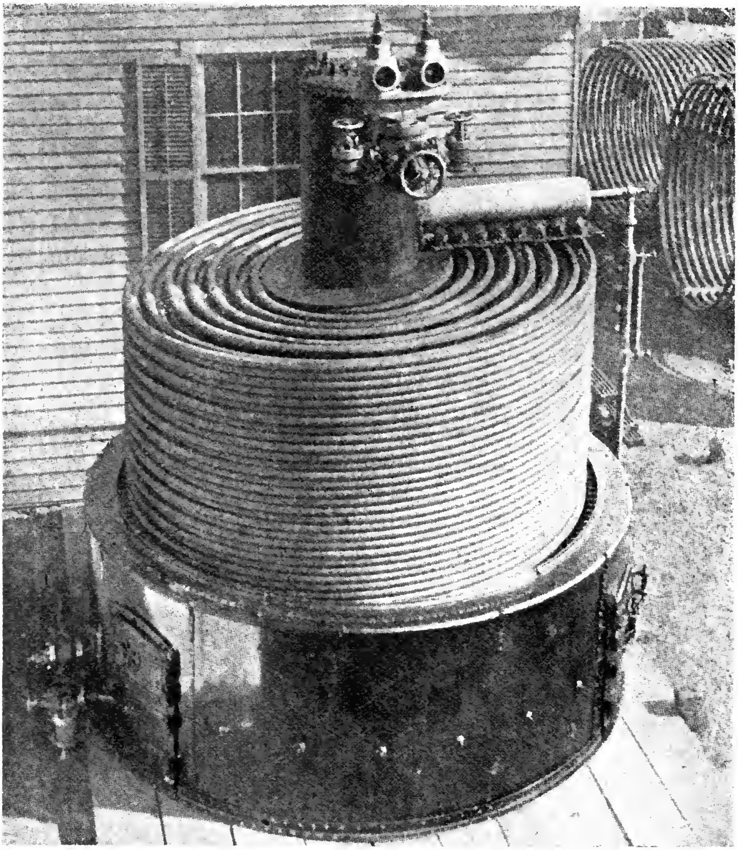


FIG. 286.

Congress in 1893. (Proceedings, Vol. ii. p. 8). Another form of Mr. Ward's coil boiler, which he calls his "Launch" boiler, has the equivalent of the stand pipes in a horizontal position, and the coil tubes proceeding in a vertical direction from them.

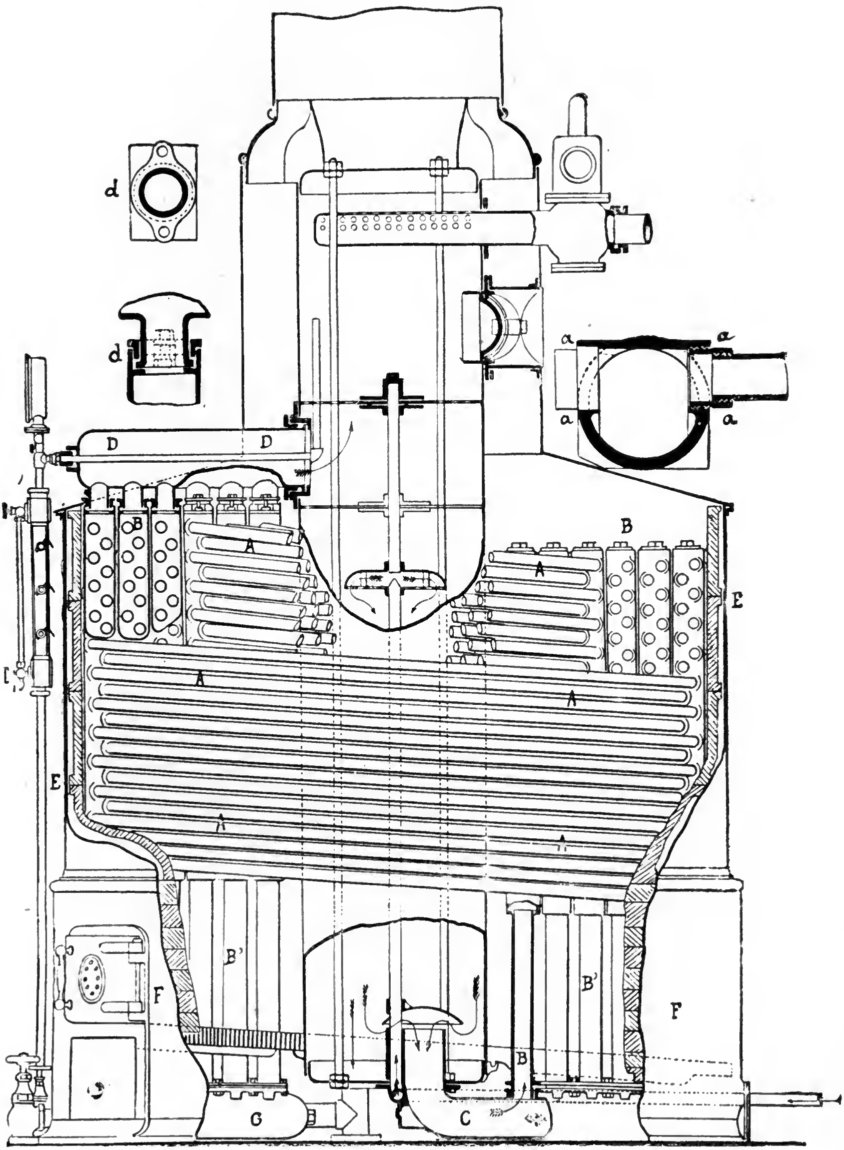


FIG. 287.

Herreshoff's Boiler.—Herreshoff's coil boiler was brought out in America in 1877. It is formed of an inner and an outer coil—the outer one being of comparatively small diameter tube—laid together to form the vertical cylindrical sides and flat top of the boiler casing. The inner coil has a slightly conical outline, the tube increasing in diameter as the coils descend towards the fire. The layers of tube are not placed close together, so that the

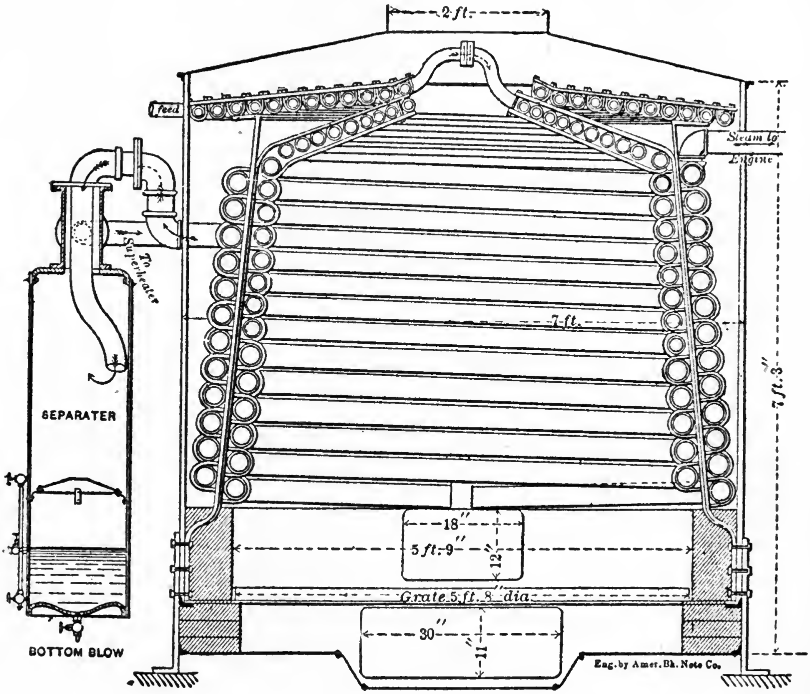


FIG. 288.

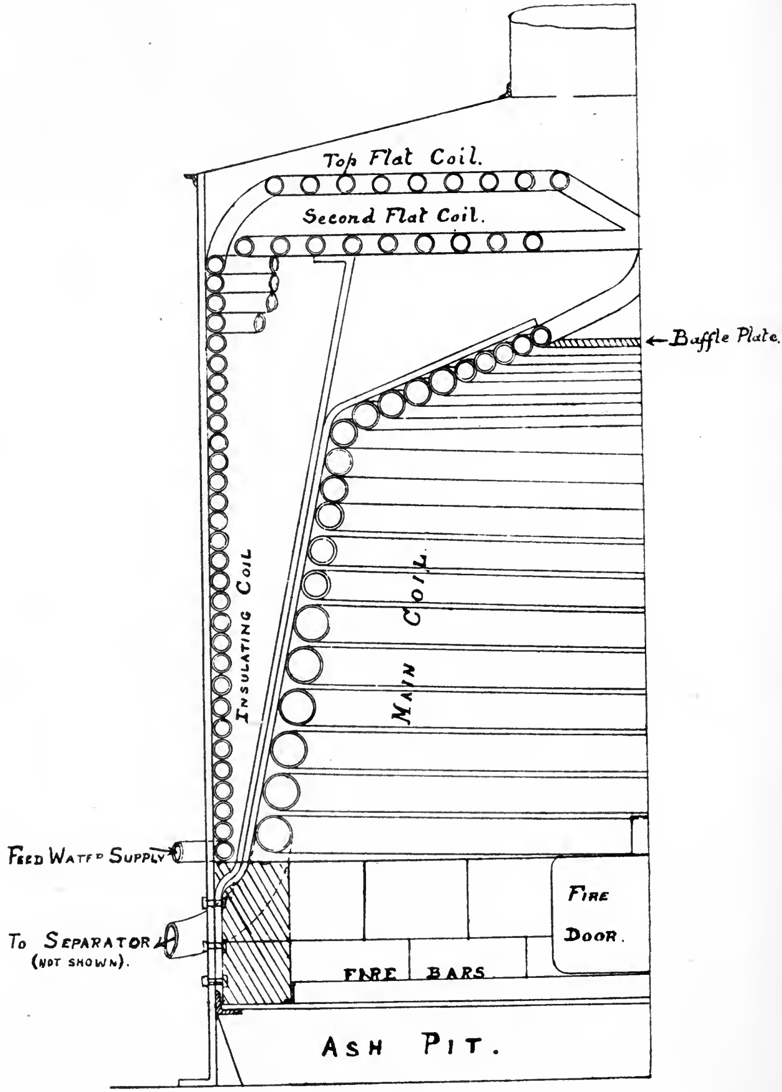
gases can escape between them. The feed water is introduced at the lowest point of the outer coil, and traversing this is introduced into the top of the inner coil, through which it traverses downwards, the steam and water being delivered into a vertical separator cylinder standing alongside the boiler casing. Fig. 288 illustrates this boiler. A later form of Herreshoff's boiler, which is formed on the type of the Belleville boiler, with flattened coil, composed of horizontal tubes with semi-circular bends—

all being exposed to heat—is illustrated by Mr. Ward, in his paper on Tubulous or Coil Boilers in Vol. ii., Proceedings of the International Engineering Congress, plate xiv. The British patent for the Herreshoff boiler was taken out in 1876 (No. 4271). It was owned and worked in this country by Mr. G. R. Dunell, who obtained a trial order for it from the British Admiralty. Fig. 289 shows the form of boiler finally adopted by Mr. Dunell and the Herreshoff Manufacturing Co., and interesting details connected with the history and performance of the boiler will be found in "Recent Practice in Marine Engineering," by W. H. Maw, Vol. i. (Text), p. 280, and in a "Report of a Board of U.S. Naval Engineers on the Herreshoff system in the steam yacht *Leila*," made to the Bureau of Steam Engineering of the U.S. Navy in 1881.

Thornycroft's Boiler.—A coil boiler was patented by J. I. Thornycroft in 1882 (No. 2102), and was referred to by him in his paper "On Water-tube Boilers" in Min. Proc. Inst. C.E., Vol. xcix, and by Mr. Ward, in the paper above quoted, as having been fitted in the Congo Mission steamer *Peace*. Fig. 290 illustrates this boiler, and that this is rightly called a coil boiler is proved by Mr. Thornycroft's patent, which is for a "coiled water-tube boiler." In the light of this it is difficult to understand Mr. Thornycroft's remark on it in Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xli., p. 74.

There are several other patents for boilers constructed of coiled tubes, but none of these, excepting the De Laval boiler mentioned later, have come prominently forward, nor do they illustrate any new features. The only ones which merit a more particular notice are those of T. Craddock, 1884 (No. 5131), and of O. Lilienthal and W. Bashall, 1886 (No. 8322) and 1887 (No. 16555). In the former of these two coils were used and the hot gases were led down between the inner and outer coils before being allowed to escape. In the latter, the coil was used to hold the fuel as in a gas-producer.

Cellular Boilers.—In the absence of an extended manufacture of reliable tubes, it was natural that in early days there should be several attempts to construct sectional boilers with a series of cells or small chambers. Where, however, intricate smithing and riveting were not resorted to, it is evident that bolts must be used to hold the parts together, and this feature, with the numerous



Top Flat Coil.
Second Flat Coil.
Baffle Plate.
Insulating Coil
Main Coil.
Feed Water Supply
To Separator
(not shown).
Fire Door.
Fire Bars
Ash Pit.

FIG. 289.

attendant joints as sources of leakage, necessarily operated against the success of such boilers.

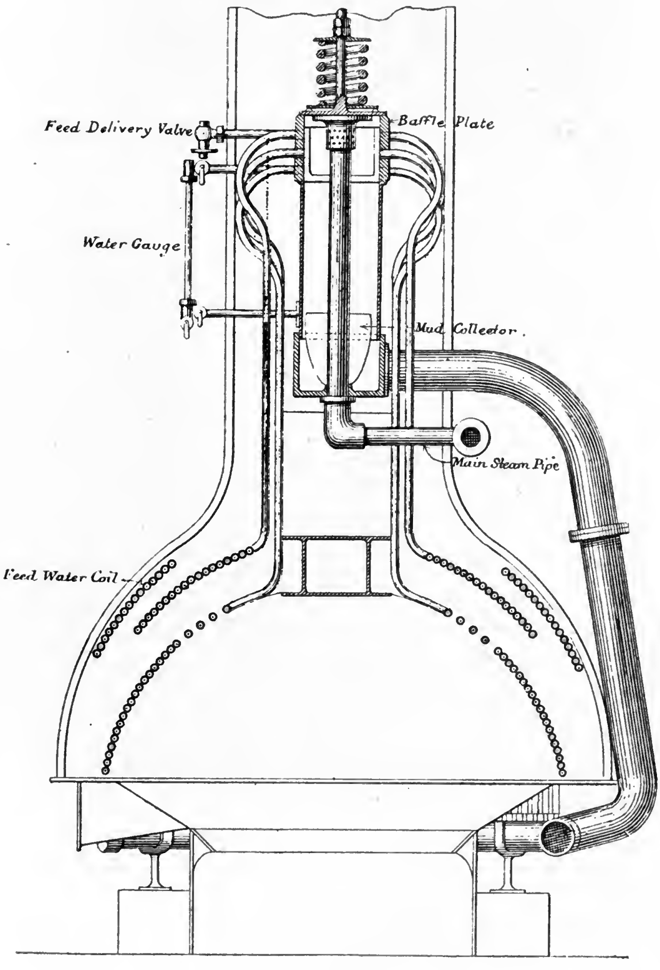


FIG. 290.

Teissier's Boilers.—The patent of J. A. Teissier, 1825 (No. 5251), contains what may be considered the first design of such a boiler, although James Rumsey mentions a cellular form of

boiler amongst his other plans. Along with the narrow chambers with flat sides and roofs in Teissier's boiler, there was the notable feature of cylindrical baskets or cages in which the fuel was placed, these being real water grates, and having the general design of such later boilers as those of Seabury and others already mentioned.

Hancock's Boilers.—Walter Hancock took out at least three patents for cellular forms of boilers in 1827 (No. 5514), 1833 (No. 6364), and 1839 (No. 7990). These in the main resulted in his constructing the boiler illustrated in Fig. 291 which was used

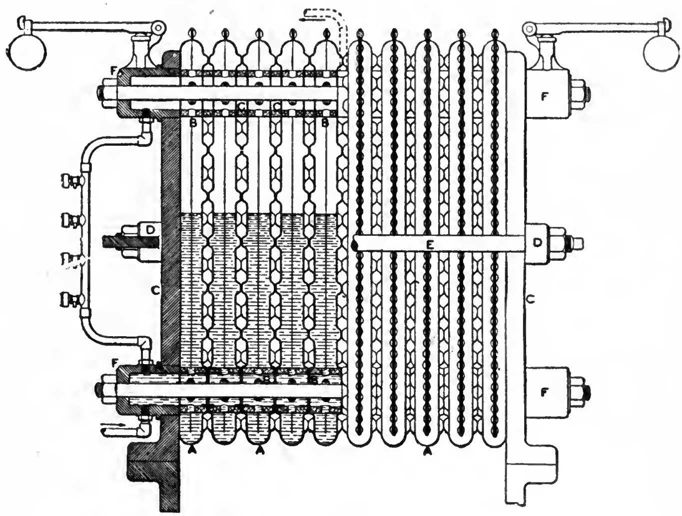


FIG. 291.

in the steam omnibuses of which he was the pioneer. This boiler was formed of a number of narrow chambers set up on edge side by side and clamped together by means of strong outside plates with bearers and tie-rods. Projections on the sides of the chambers caused spaces to be formed between each pair of chambers through which spaces the hot gases were passed. Larger projections were also formed by hammering the plates into dies,[1] which formed the top and bottom transverse com-

[1] See "Reminiscences of Steam Locomotion on Common Roads," by Sir F. Bramwell, British Association Oxford. 1894. *Engineer*, 17 Aug., 1894, p. 152, etc.

munication between the chambers. A similar construction was patented by Wm. Church in 1835 (No. 6791), but this was evidently not the boiler used by Church in his coach (see ante, p. 424).

Thomas Brunton in 1831 (No. 6106), and J. McCurdy in 1835 (No. 6819), both patented cellular forms which might be used as heaters connected with a larger vessel or "boiler."

Anderson's Boiler.—E. H. Collier, 1836 (No. 7145), and Sir J. C. Anderson, 1837 (No. 7407), and 1846 (No. 11273) also followed with designs of boilers composed of flat leaves or cells, all these being coupled as to water and steam in parallel, although the gases had to pass, in some cases, over the surface of the cells in rotation.

McCurdy's Boiler.—J. McCurdy's patent of 1838 (No. 7890), however, provided for the coupling of the leaves in series for the flow of the water. He gives minute details of the dimensions and performance of this boiler.

Zander's Boiler.—H. Zander in 1839 (No. 8111) patented a cellular boiler made of cast iron, in which he has been followed by the Harrison and the Exeter Boilers, both of which are properly cellular boilers. James Johnstone, 1843 (No. 9706); Chas. Cowper, 1853 (No. 1247); and A. V. Newton, 1853 (No. 2188), also add to the list of designs of this class, but not of those which were used.

Lamb and Summer's Boilers.—The boiler patented by Andrew Lamb and W. A. Summers, 1848 (No. 12362), 1858 (No. 2815), and 1859 (No. 2143), although of the tank or box design, is interesting from the cellular form given to the return flues or passages. The construction of these cellular passages is shown in Fig. 292. This boiler was at one time used to some extent in steamships.[1]

Rowan and Horton's Boiler.—In the patent boilers of J. M. Rowan and T. R. Horton, 1858 (No. 856), 1860 (No. 332), a somewhat similar form of openings or passages was combined with flat leaves or cells which contained water. In addition to these vertical openings there were vertical or horizontal tubes passing through the water spaces, which tubes were used for conducting the hot gases, or sometimes as water-tubes, and

[1] See Proc. Inst. Mech. Eng. 1851. p. 9.

thus adding to the area of heating surface. The cellular openings were made by bending and welding double-angle or channel iron, and not, as in Lamb and Summer's boilers, by rivetting a **U**-shaped piece of plate to the sides of the openings.

This boiler is illustrated in Figs. 293, 293B. It had for about 12 years a very successful employment in steamers, of which some particulars are given in Chap. IX., but the cost of construction caused it to give way to forms made almost wholly of tubes (see p. 431 ante) as soon as tubes were manufactured of such quality

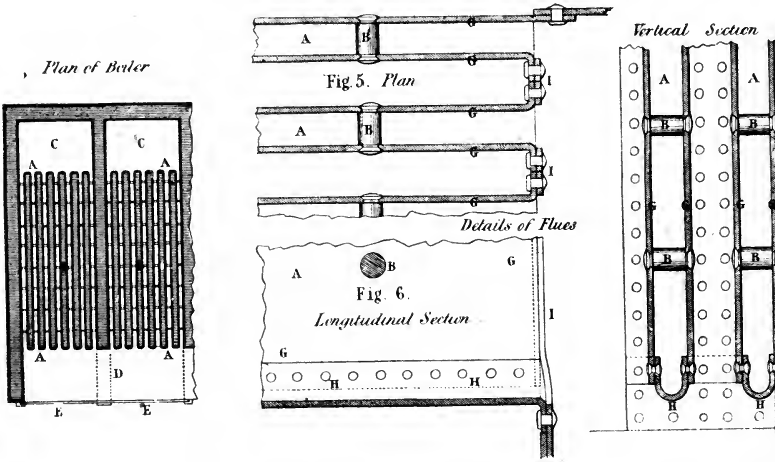


FIG. 292.

as would enable them to stand high pressures of steam in water-tube boilers. The boiler of H. Gourlay and E. Kemp, 1860 No. 779), to some extent resembled the Rowan and Horton Boiler, and on this account it was not proceeded with. The patents of T. W. Miller, 1860 (No. 1396); G. Davies, 1860 (No. 3008); W. H. James, 1862 (No. 3081); J. H. Johnson, 1865 (No. 2610); J. Bernard, 1866 (No. 1410); C. L. Carville, 1867 (No. 1637); J. Witherspoon, 1884 (No. 4657), for cellular forms of boilers, demand no further notice. In fact the day for this class of designs may be said to have passed away, except for some special application, such as the small generators required for motor-vehicles.

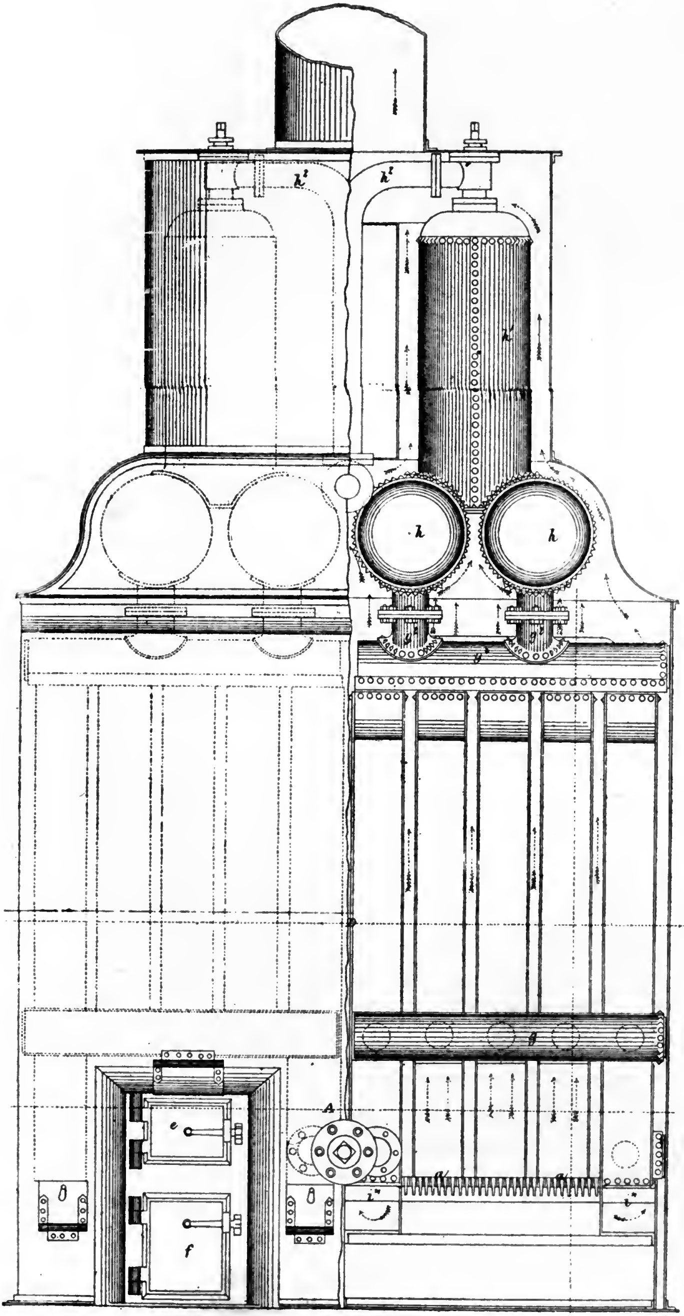


FIG. 2[illegible]

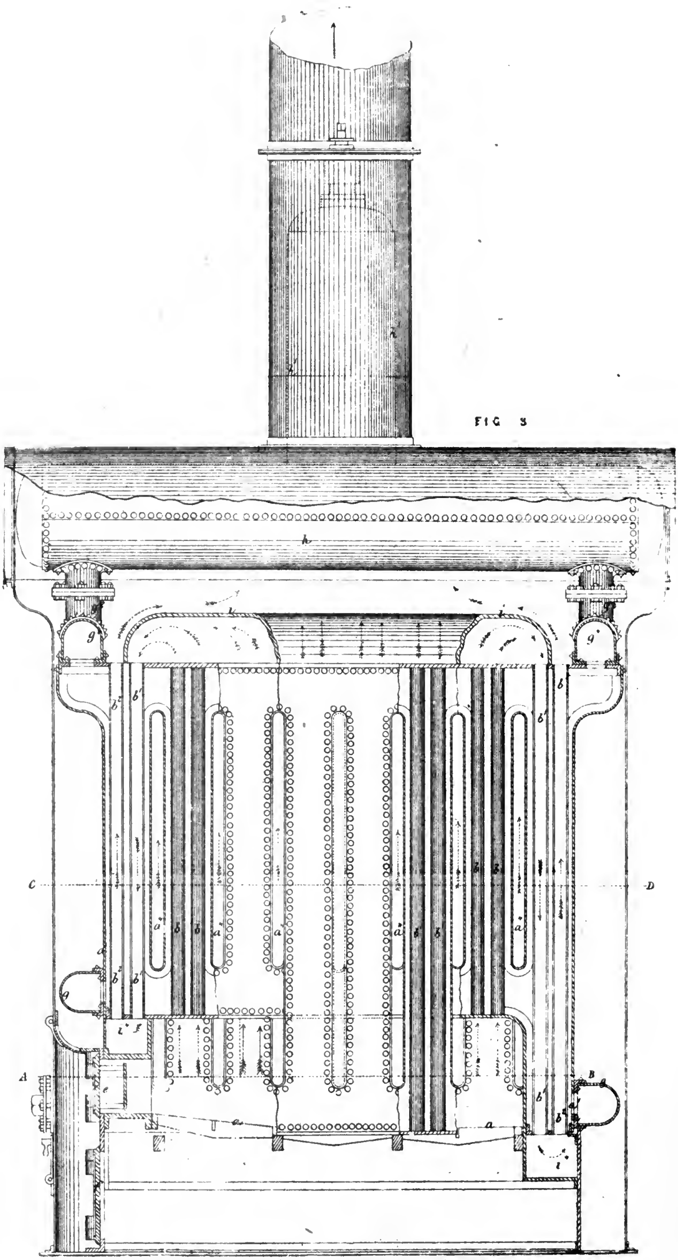


FIG 293B.

Panhard and Levassor's Boilers.—The cellular boiler patented by R. Panhard and E. Levassor, 1887 (No. 16903), has been used for this purpose, as well as others of different design, such as Serpollet's, Thornycroft's, Simpson and Bodman's, and De Laval's.

Revolving Boilers.—The varieties of designs in which the steam-generating portion of a boiler is caused to revolve in a furnace date from 1825, in which year J. Thompson and J. Barr (No. 5192) proposed such a design of boiler. They were followed

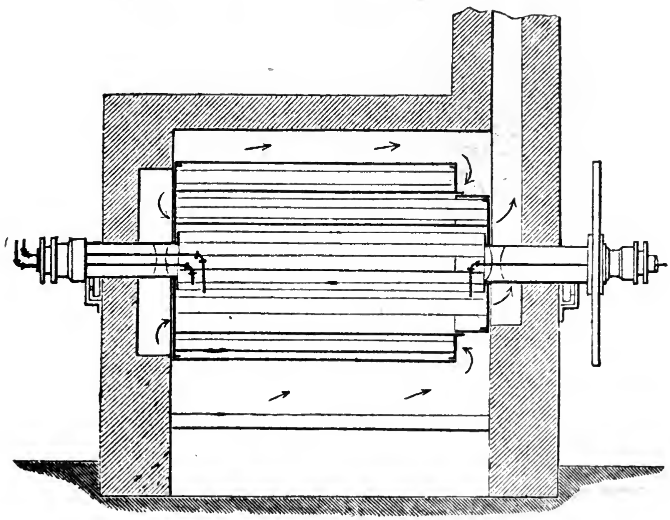


FIG. 294.

by W. T. Yates in 1834 (No. 6547), G. Duncan in 1853 (No. 502), D. Dunn in 1855 (No. 1223), G. Scott in 1857 (No. 2585), this being a coil of tubes and not a cylindrical chamber which was made to revolve, Dr. F. Grimaldi in 1860 (No. 1927) and 1861 (Nos. 1641 and 3207), J. H. Johnson in 1865 (No. 607), and the Pierce boiler, which was introduced in America and was amongst the boilers submitted to systematic tests at the International Exhibition in Philadelphia in 1876.

Pierce Boiler.—This boiler is illustrated in Fig. 294, and some of the results of its tests will be found in the tables in Chap. IX.

The most recent proposals in this direction seem to be those

of R. Heber Radford in 1892 (No. 153), and A. J. Boult, 1893 (No. 12059).

Porcupine Boilers.—A small class of boilers has received the name of "porcupine boilers" from the peculiarity of their form or appearance. They consist generally of a central chamber from which cones or tubes project radially in all directions. Sometimes the tubes have the straight form of Perkins' pendant tubes placed horizontally with an internal circulation tube, though in other cases the internal tube is absent. In some cases the tubes are bent to form a series of loops all round the central chamber.

Gibbs' Boiler.—The earliest of these is that of the patent of Jos. Gibbs and A. Applegarth in 1832 (No. 6318) in which cones were used to project into the flue space in order to increase the heating surface.

Joseph Barrans in 1852 (No. 41) also proposed to have cup-shaped projections or deep corrugations in the plates of his fire box, and Henry Bougleux, 1856 (No. 2793), and 1857 (No. 50), repeated the same idea, making his projections, however, more of the shape of a thimble, and in some cases piercing them by a tube for the products of combustion.

Fletcher's "Thimble" Boiler.—H. A. Fletcher in 1869 (No. 998) patented a boiler of this class which was described and illustrated in *Engineering*, Vol. viii., p. 38.

W. Clark (for M. Hervier), 1882 (No. 4669), and E. S. T. Kennedy, in 1885 (Nos. 1273, 5768, 13800), 1886 (No. 12282), 1887 (No. 11673), and 1888 (Nos. 7065, 12780), repeat the design, whilst A. M. Clark, 1883 (No. 264) has a modification of it with a number of bent tubes forming radial loops from the central chamber.

The most complete examples of the system are E. S. T. Kennedy's patent of 1893 (No. 3486); the Minerva and Hazleton boilers brought out in America and the "Climax" boiler, also an American invention, but now manufactured in England.

Hazleton Boilers.—There are two forms of the Hazleton boiler manufactured in America, one called the Hazleton Tripod boiler, made by a Company of that name in Chicago, and the other called the Hazleton boiler, made by its Company in New York. There is not much difference between the designs and Fig. 295

will suffice to illustrate both. The "porcupine" tubes which project horizontally from the vertical stand-pipe chamber have no internal circulating tubes. The difference between the two "Hazleton" boilers consists merely in details—the "Tripod" boiler having a branch man-hole leg near the bottom of the

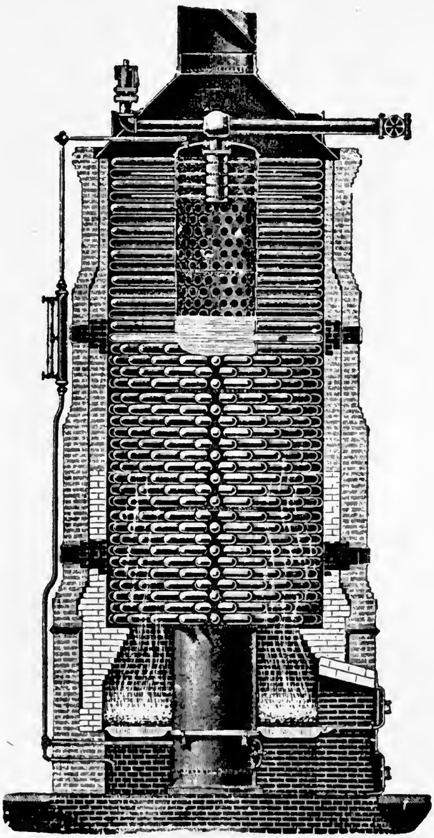


FIG. 295.

central chamber and three shorter branches, like enlarged "porcupine" tubes near the top, with a steam and water separator in a part of the central chamber projecting above the tubes. The Hazleton boiler illustrated shows the more simple construction.

Minerva Boiler.—In the case of the Minerva boiler shown in Fig. 296 each of the horizontal porcupine tubes has an internal circulating tube which projects from an inner shell in the central vertical chamber, but it seems apparent that in this boiler these internal tubes are used for conducting the steam into the central inner chamber, whilst the water enters from the outer division of that chamber to the larger porcupine tubes. This cannot be

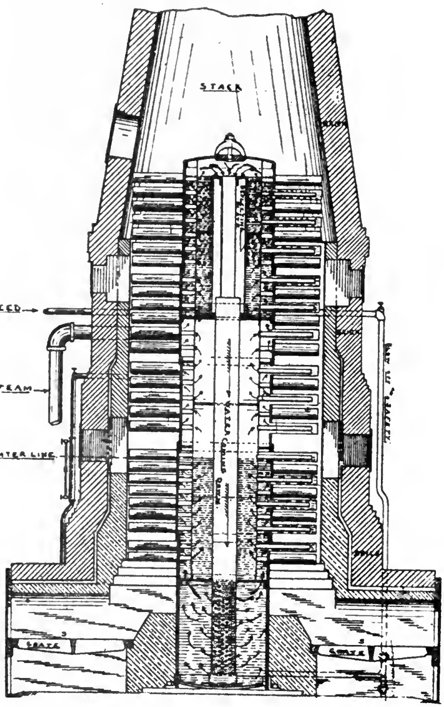


FIG. 296.

so good an arrangement as that which uses the inner tube for water, and allows the steam to escape from the mouth of the outer tube in which it is generated. The vertical chamber of the Minerva boiler is also divided by horizontal partitions to form a water chamber, in which the feed enters, above the steam space. This presents water to the escaping gases which may thus be cooled down below the temperature of the steam.

The steam pipe can also be placed at a more convenient height than the top of the boiler. All the water in the top chamber can be discharged into the bottom chamber almost instantaneously by opening two valves on a special pipe.

Climax Boiler.—The Morrin "Climax" boiler has a central vertical cylinder with radial loop-shaped tubes projecting from its sides round its complete diameter, these tubes being placed each at a slight inclination so that one end enters the cylinder at a higher level than the other in order to favour circulation. Diaphragm plates are introduced near the top of the cylinder in

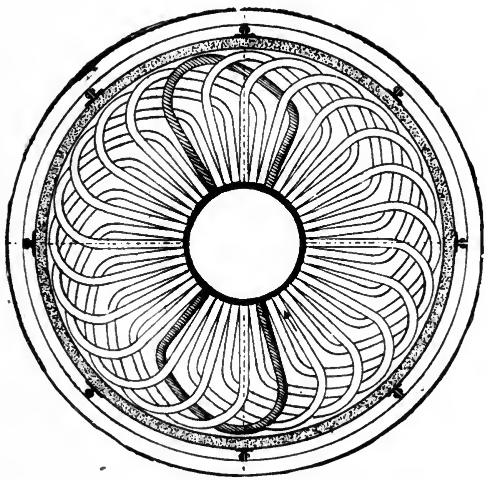


FIG. 297.

order to cause the steam to pass through several layers of the radial tubes on its way to the steam dome, and thus to dry and partially superheat it. Above the radial tubes a coil is placed in order to heat the incoming feed water. Figs. 297 and 298 illustrate this boiler and fully demonstrate its mode of construction and the manner in which the looped tubes are arranged. This boiler was patented by T. F. Morrin, of New Jersey, in 1884 and subsequent years, and the manufacture of it in Britain is in the hands of Messrs. B. R. Rowland and Co., Limited, of Manchester.

Miscellaneous Designs.—There are some designs which for various reasons are more suitably considered apart from the

classes which embrace a number of boilers which have approximately the same general features, than as taking a place amongst

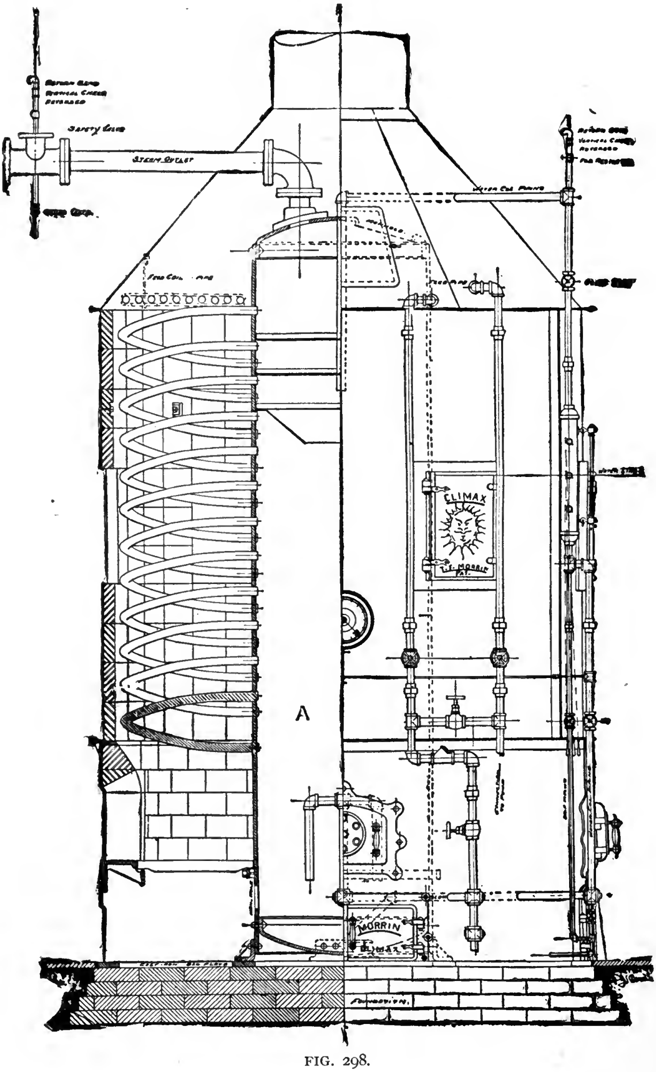


FIG. 298.

them. The following examples seem to be the most deserving of notice:—

In 1836 (Nos. 7059, 7242) Jacob Perkins patented a boiler in which straight tubes, hermetically sealed at both ends, and containing a small quantity of water amounting to about $\frac{1}{1800}$th part of their capacity, projected at their lower ends into the combustion space and at their upper ends into the water in a boiler. The small quantity of water in these tubes was rapidly transformed into steam of high pressure, and transmitted heat into the water in which their upper ends rested. In the later patent he carried these tubes through the boiler and used them as stays or tie-bolts. A modification of this plan was patented by A. M. Perkins in 1855 (No. 2755) in which horizontal parallel coils were used, instead of the straight tubes for the water heaters. This plan was repeated by Longbottom and Longmaid in 1856 (No. 220). There was not much to recommend it as a boiler design, but it was afterwards utilised by Jacob and A. M. Perkins in the construction of military field bakers' ovens, and it has been re-patented by Fraser, Harris, and Perkins in 1893 (No. 1206), and by E. Herz, 1893 (No. 1467), and others.

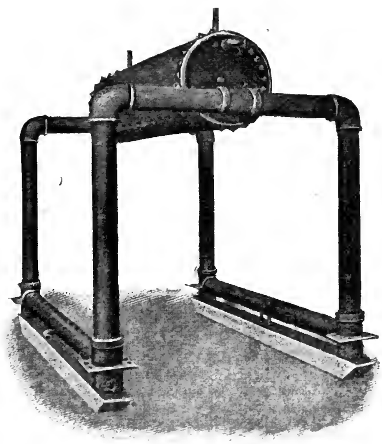


FIG. 299.

Roberts and Almy Boilers.—Two designs, which to some extent resemble each other, are those of the Roberts Boiler and the Almy Boiler, both brought out in America.

The Roberts Boiler is shown by Figs. 299, 300, and 301. It is composed of a frame, formed by downcomer tubes from the central steam drum to the lower water pipes or drums, as shown in Fig. 299. Within this frame a number of flat coils of generating or "upflow" tubes are placed, with a vertical position starting from the water pipes and forming the sides of the furnace. These are shown in position in Fig. 300. In addition to these, super-heating and feed-heating coils are placed above these coils on each side of the steam drum and on the outside of the boiler

on the two sides as shown in Fig. 301. A casing envelopes the whole. This boiler was introduced in America by Mr. C. E. Roberts in 1879, which date shows that Mr. Roberts was not, as he claimed,[1] "the first inventor of boilers involving an upper steam and water drum and two lower water drums at each side of the fire, connected by downflow pipes." Fig. 302 illustrates the boiler made by the Almy Water-tube Boiler Co., of Providence, New York, which bears a certain amount of resemblance to the Roberts Boiler.

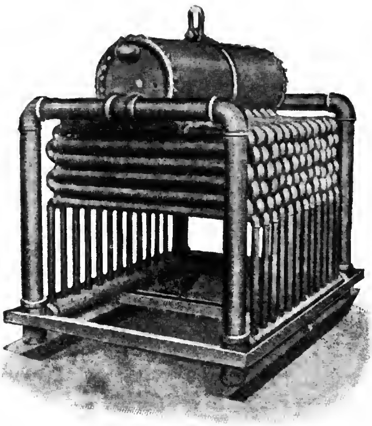


FIG. 300.

Serpollet Boiler.— Patents were taken out in Britain by Serpollet Frères et Cie. in 1880 (No. 1067), 1887 (No. 14710), 1889 (No. 5197), 1890 (No. 12164), and 1894 (No. 997), for different forms of flash boilers, the last being the form adopted in France for use in their steam automobiles. This boiler is formed of tubes having considerable thickness of metal, with a very small, or "capillary" passage for the water or steam. In one form these tubes were flat in section and bent into a coil shape as shown in Fig. 303.

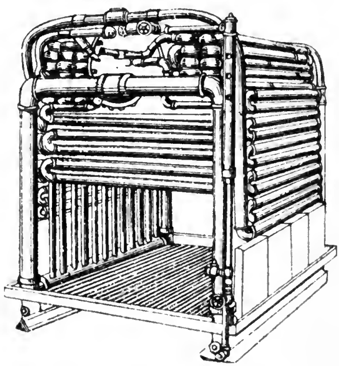


FIG. 301.

A later form, however, has the tubes straight, but of a horseshoe section, giving the capillary space a crescent form, except at their ends, which are left round in order to make connection with the bends.

[1] Proc. Internat. Engineering Congress, Chicago, 1893, Vol. ii., p. 74.

This design is shown in Fig. 304. Through the small passages or slits in the pipes water is forced and, the quantity being so small in relation to the mass of metal which retains a considerable amount of heat, the water is almost instantaneously flashed into steam, which is superheated by further passage through the heated tubes. By varying the rate at

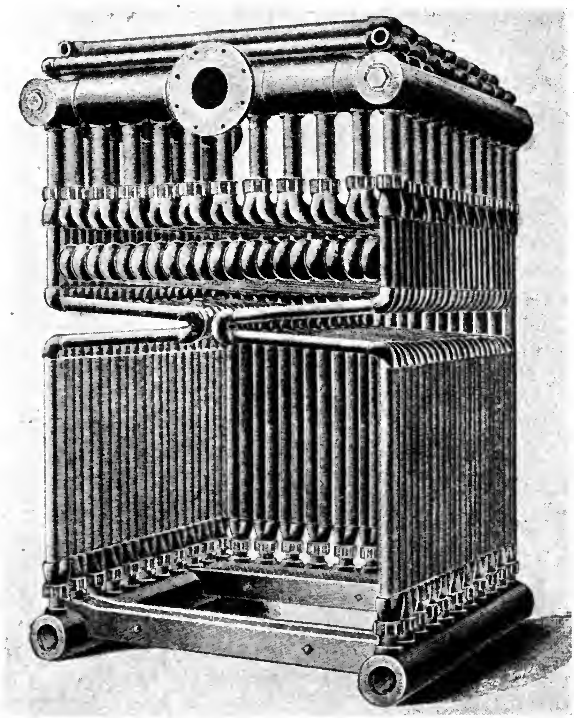


FIG. 302.

which water is forced in, the quantity of steam produced can be altered at will. The tubes are made of steel and are tested to 200 atmospheres, the working pressure of the boiler being about 350 lbs. per sq. inch. It is sometimes urged against this system that the high temperature to which the tubes are exposed causes comparatively rapid oxidation and that cleaning the narrow passages by means of the use of an acid solution has to

be resorted to, but it does not appear on what records this objection is founded.

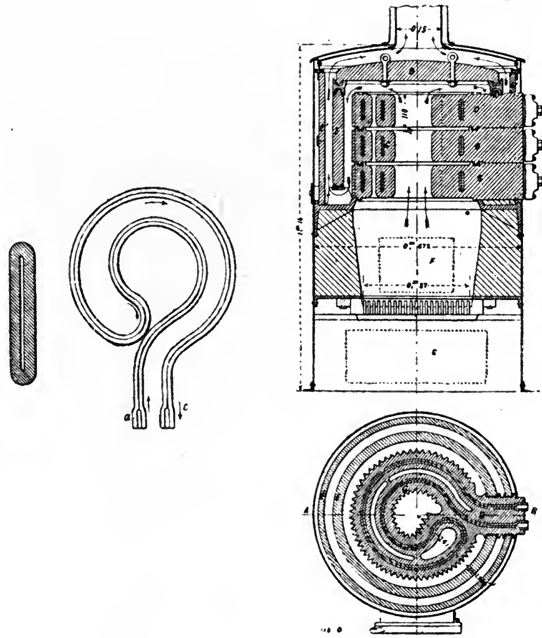


FIG. 303.

Thornycroft Boiler.—A modified form of Thornycroft Boiler, which has been used by the inventor for steam automobiles, was patented in 1894 (No. 18,838). A somewhat similar design is illustrated in Bertin and Robertson's "Marine Boilers" (page 314) and is ascribed to Leblond and Caville (1896), and it is not unlike the stationary boiler of Rowan and Horton's patent of 1869. Leblond and Caville's British patent is dated 1895 (No. 9444).

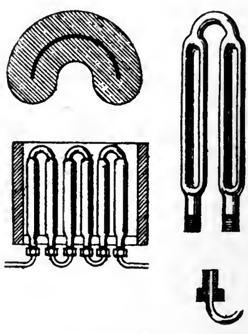


FIG. 304.

De Lavals' Boiler.—Some particulars of an interesting boiler invented by Dr. de Lavals, of Stockholm, have appeared in the *Electrical Engineer* of

New York (November 11th, 1897), and in *Engineering* of November 26th, 1897 (pp. 644-645). This boiler is intended for use in conjunction with the De Lavals steam turbine, the peculiar design of which enables steam of very high pressure to be used without causing any attendant difficulties as to tight joints or lubrication to be experienced in the engine. The different types of these boilers which have been constructed work at pressures of from 50 to 220 atmospheres, one shown in action at the Stockholm Exhibition in 1897 worked at 1,700 lbs. per square inch pressure, the temperature of the steam being about 600 F. The steam-space and water-space in the boiler are very small, and as a consequence the boiler is extremely sensitive to variations in the load, so that the arrangements for working it present the nearest approach to complete automatic regulation which has been made. The boiler consists of a single tube, of solid-drawn malleable iron of comparatively small diameter, wound in concentric spirals between which the gases of combustion escape. The tubes are submitted to a hydraulic pressure of more than double the working steam pressure before being used. The grate is shaped like a ring and has a revolving motion, and the coals are filled in centrally from boxes above the boilers. These boxes need not be filled more than once in every two or three hours, but the layer of fuel in the furnace is kept automatically at a constant thickness. The air necessary for combustion is forced into the furnace by means of a fan which is coupled direct to the driving shaft of the turbine, and, by means of an apparatus regulated by the steam pressure and acting on the valves of the blast, the combustion is regulated according to the quantity of steam consumed. The feed water is pumped continuously into one end of the tube and passes through the spirals one after the other with considerable velocity, forming steam which is superheated in the final portions of the spirals from which it passes to the turbine, there being no steam chamber or reservoir. Special regulating apparatus is also employed to cause the feed pump to feed into the boiler as much water as the turbine uses as steam, so that the proportions of water and steam in the boiler and the degree of super-heat are kept constant. The exceedingly powerful circulation of water in the boiler renders the heating surface very effective, and this, coupled with the fact

of the small steam and water spaces referred to, has made it possible to bring the dimensions of the boiler within a small compass. It is stated that a combined 100 horse power turbo-generator with suitable boiler and condenser occupies a floor space of only 18 ft. 6 in. by 11 ft. The boiler is self-contained, requiring no brickwork except the foundation. The air supply passes through an outer shell, whereby it absorbs the radiant

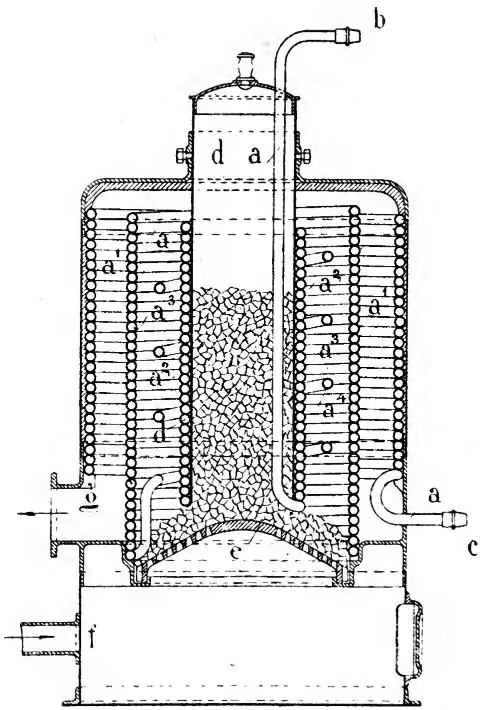


FIG. 305.

heat, or at any rate prevents loss by radiation, and the use of the air-blast also has tended to reduce considerably the size of chimney required. No illustration of this boiler has been as yet made public, except that in Dr. de Lavals' British patent, Specification No. 14884-1895 (see Fig. 305), but the description shows that it embodies a very great advance towards a perfect steam-generating apparatus.

Simpson and Bodman Boiler.—Early in 1898, Messrs. D. H. Simpson and W. L. Bodman communicated to the Liverpool Centre of the Self-Propelled Traffic Association an account of various interesting trials and experiments carried out by them to determine the best types of boilers and motors for steam road vehicles. Probably the most interesting attempt to construct an efficient flash boiler is the one which is illustrated by Fig. 306, in which the Row patent indented tubes were employed, their wavy form, resulting from the tubes being pressed between dies alternately at right angles, causing the water to come into intimate contact with the heating surface. The tubes used were of solid-drawn steel, with the ends swaged down so as to form practically stout double-ended gas bottles. Twenty-two such tubes were used in the construction of a boiler to evaporate about 300 lbs. of water per hour. They were coupled in series over the fire, being connected by steel tube bends. The ends of the main tubes were screwed with eleven threads to the inch, and the bends fourteen to the inch. A strong hexagon nut, screwed to fit the bend at one end and the tube at the other, being used to draw the bend up the tube, the difference in threads gave a pull equivalent to an ordinary union nut with 51 threads per inch, and the strength of 14. Forty-four joints made in this way stood 800 lbs. hydraulic test at the first time of screwing up.

The tubes are placed horizontally over the fire in a suitable casing. Connected to the steam outlet end is a double-ended steel gas bottle, which has a tube passing through its centre, through which the feed water passes in its way to the generator. It is thus heated, removing some of the super-heat of the steam, and increasing the duty of the boiler by the introduction of hot feed. After the boiler has been standing, or when the steam is very hot, water is sprayed into the drum, when it is evaporated by the extra heat in the super-heated steam, and passes on to the engines. This system of injecting water into the steam and cooling it down to a reasonable temperature, while still leaving the boiler hot as a reserve of heat, has, according to Messrs. Simpson and Bodman, overcome one of the greatest difficulties in this type of boiler. The system of starting and working is explained by

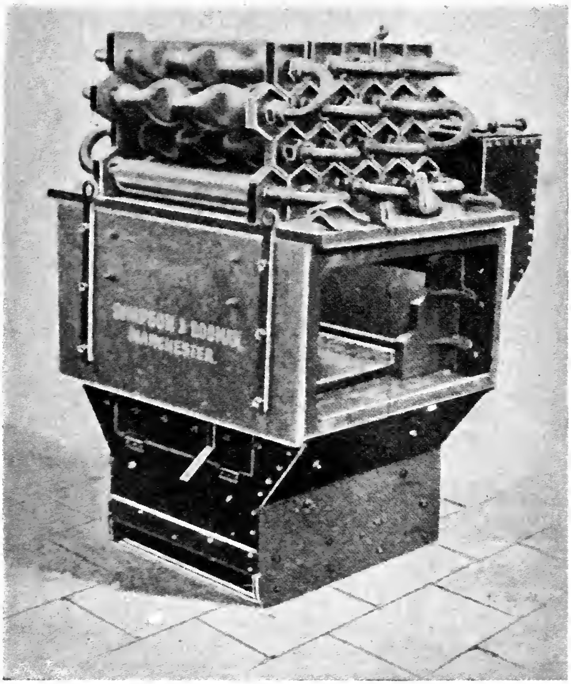


FIG. 306.

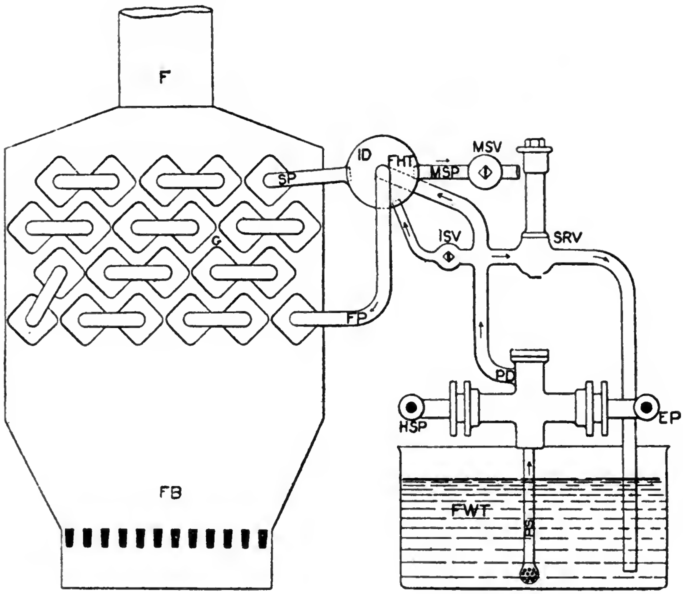


FIG. 307.

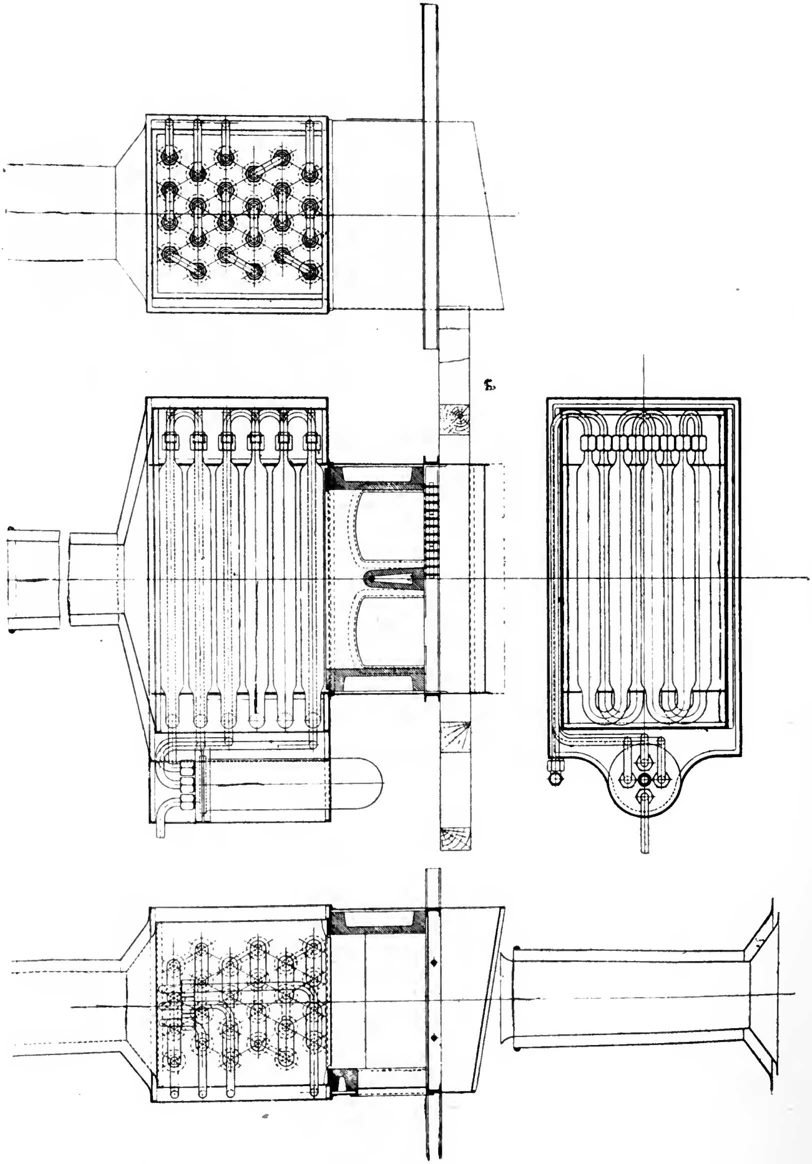


FIG. 308.

the diagram Fig. 307 with the following notes :—The generator is raised to a black heat, say 800° F. A stroke or two of the hand pump H.S.P. sends the water up the pipe P.D. The injector valve I.S.V. is opened, and a small amount of water allowed to enter the drum I.D. The valve I.S.V. is then closed, and the water travels through the feed heating tube F.H.T. in the centre of drum I.D., and on through the feed pipe F.P. into the generator. The superheated steam then passes into the drum I.D., where any excessive superheat is extracted by the feed water passing through the central tube, and by the water injected into the drum. The hand pump is worked until the water relief valve S.R.V., which is set to working pressure, starts returning the surplus water to the feed water tank F.W.T. Then the main stop valve M.S.V. may be opened, starting the engines, which work their own pumps E.P., keeping up the supply of water, any surplus being returned by the relief valve.

Controlling the feed by a steam pump, used in conjunction with a live steam feed heater, the water from the pump exhaust being drained back to the feed tank, was preferred to any automatic gear. Fig. 308 shows the most recent form of this boiler from the working drawings. The illustration shows a boiler composed of 12 "members" of weldless steel tubes—these "members" being **U**-shaped, the straight portions being indented on the Row plan, and the bends being smooth and smaller in diameter. The only joints are thus made at the front of the boiler, or at one side, the system of making the joints being that introduced in the Haythorn boiler. The water is fed direct from the pump into the top row of tubes in the generator, and issues from the second row, having traversed the four uppermost **U**-tubes. It then passes through a **U**-shaped tube inserted in the steam regulating drum, and thence passes to the bottom row of tubes and passes out from the fourth row from the bottom as superheated steam, which is collected in the steam drum.

The patents for the Simpson and Bodman boiler are dated 1896 (Nos. 4485 and 4486).

Some particulars of tests of this flash boiler are given in Chap. IX., but by forcing, the evaporation can readily be increased to 500 lbs. of water per hour.

Boilers with Gas Producers.—Several designs have been proposed in which the mass of fuel, instead of being wholly spread on a grate, is held by portions of the boiler, which thus enclose it somewhat in the manner of the walls of a gas producer. The labour of stoking is thus rendered easier, and the fuel before reaching the zone of combustion is partially heated, and may even be partially distilled, the gases thus given off being subsequently ignited when means for the admission of air are present along with sufficient combustion space. The attempt to combine the functions of a gas producer with those of a boiler is not, however, a very promising one, if for no other reason, because an efficient gas producer demands combustion at a comparatively low temperature, whilst the utilisation of the fuel in a boiler requires that, as we have seen, combustion shall take place at the highest possible temperature, and it will be extremely difficult to reconcile such opposing conditions in one apparatus.

Part of the idea is contained in Paul's patent of 1824 (see p. 361 ante), whilst William Church in 1832 (No. 6220) proposed a boiler composed of vertical tubes, set in circular rows round a grate, the fuel being filled in from the top ; and C. Johnson in 1868 (No. 2021) proposed another form for a similar arrangement. In 1884, B. C. Sykes and T. Briggs (No. 2709), and J. W. Macfarlane and J. J. Coleman (No. 12497) combine boilers with enclosed gas producers fed from above.

In 1886, O. Lilienthal and W. Bashall (No. 8322) have a coiled water-tube boiler with the fuel arranged as in a gas producer enclosed in the coil. Their subsequent patent in 1887 (No. 16555) was abandoned. J. J. Barclay in 1889 (No. 11864) combined a shell boiler with a similar arrangement for the fuel[1] and G. H. Taylor, 1889 (No. 14708) had a gas producer combined with a vertically inclined water-tube boiler. About 1886 B. H. Thwaite proposed the combination of a boiler with his gas producer, but in this case[2] the boiler was placed above the gas producer and formed the combustion chamber for the gas which was produced below.

[1] Another will be found illustrated in *The Mechanical Engineer* of 9th April, 1898, page 368.

[2] See Min. Proc. Inst. C.E., Vol. lxxxiv., p. 105.

Other designs which have been proposed are those of W. Schmidt, 1893 (No. 564); L. Bemelmans, 1893 (No. 1290); E. Herz, 1893 (No. 1467); G. H. Taylor, 1893 (No. 7510); C. A. Allison, 1893 (No. 9077); L. Benier, 1893 (No. 64), 1894 (No. 6744); J. M. White and J. Timmins, 1894 (No. 7934); S. S. Bromhead, 1896 (No. 4674); De Laval, 1895 (No. 14884); Newton, 1895 (No. 22023), &c.

The latest proposal is that of Professor W. H. Watkinson in 1898 (No. 13328) who uses the vertical tubes of his boiler, which is described in his specification of 1896 (No. 15721), to form two sides of a gas producer. The other two sides may be built of brick or of walls of tubes. The fuel is fed in at the top through a hopper placed between the two horizontal drums from which the tubes descend. A special trough-shaped casting with grids along the sides forms the grate. In outline the boiler is similar to that of the land boiler shown in Rowan and Horton's specification of 1869, two of these latter elements (used also by the author in 1894, No. 8170) being placed side by side, but Professor Watkinson arranges his vertical tubes very closely side by side in order to allow only very thin sheets or streams of hot gases to pass through. The object of this arrangement is to imitate the well-known cooling action of wire-gauze on flame, but unless some means were provided for re-igniting the cooled gases on the far side of such a wall of tubes it is probable that much of the combustible gas might escape unconsumed. It is well-known that whilst a flame cannot pass through wire gauze, it is still possible to ignite the gases on the opposite side of the gauze, and this result will even be automatically accomplished as soon as the wire gauze becomes red hot. If complete combustion took place before the gases were passed through, the first row of tubes there would completely screen the heat from the rest of the boiler surfaces.

Several designs of boilers due to French inventors will be found alluded to in Bertin and Robertson's "Marine Boilers" at page 282, and in "Les Chaudières Marines" by M. L. De Chasseloup-Laubat in the Memoires de la Société des Ingénieurs Civils de France, for April, 1897.

General Observations.—There can be little doubt that in proportion as we apprehend the importance of the principles which are dealt with in the preceding chapters, we shall be able to

estimate the value of the different designs that are proposed, according as they exhibit the varying degrees in which true principles are applied, and to discriminate between different designs. In many of the cases which have been before us we have no record of the pressure of steam at which it was intended to work the boiler, so that only the forms can be compared generally in view of the action of steam raising, and partially in relation to strength. It must not be forgotten that whilst the boiling of water in an open vessel, or at atmospheric pressure, is an action which proceeds strictly on natural lines, when we employ a closed vessel and higher pressures of steam we have introduced conditions which render steam-raising more or less an artificial process, which must be conducted in accordance with scientific principles, the carrying out of which process demands frequently the highest engineering skill for its successful manipulation and control. On this account it is apparent that one without training or experience can no more handle or judge of a scientific steam generating apparatus, than can an ordinary mill-wright manipulate the finer mechanism of a watch or a delicate electrical machine. Actions that are incongruous with steam generation should be rigidly excluded from the steam generator, and, to take one marked instance, it is incontrovertible that the separation of solid matters of any description from the water is not an operation which should be carried on in an apparatus designed for steam generation. All treatment of the water from which steam is to be produced, whether for purification or for the prevention of incrustation or corrosion, should be carried out in vessels external to the boiler.[1] It is absurd to expect that an efficient steam generator should also act as a precipitating, filtering or mud-collecting apparatus. The conditions which are essential to the highest efficiency in generating steam are sufficiently complex and onerous to demand that the boiler shall be entirely devoted to them.

After the problem of combustion is mastered, there are two great factors which govern all considerations leading to the determination of the best design, viz. :

[1] On this subject see the excellent Report on the Purification of the Feed Water of Locomotives presented by Mr. J. A. F. Aspinall to the Sixth Session of the International Railway Congress held in Paris during 1900.

1st, the movement of the hot gases, or the application of the heat presented for transmission in the best way, and

2nd, the movement of the water, or circulation of the heat recipient, so that heat may be most freely received and steam most readily liberated and the boiler surfaces preserved.

There are sub-factors, such as strength (involving, of course, safety), lightness, durability and economy, which include the question of the necessity for, and facility of executing repairs, but there is no reason why these should not be easily provided for if they are kept subordinate to the others. It has been too much the practice to place those first which should be subordinate, and those last which should be first. In the past, with chimney draught, facility of combustion was no doubt naturally the first consideration, and the most convenient arrangement probably was one that permitted the gases to continually ascend. Hence horizontal or horizontally inclined tubes seemed to present their surfaces in the best position to the stream of hot gases. Even then, however, good results were obtained with vertical tubes or surfaces by directing the course of the gases to and fro horizontally and even downwards. With mechanically moved gases we can command their direction of movement, and have the opportunity of considering primarily the means of utilising to the best advantage, and even of aiding, the movement of the water and steam.

Different theories of the course followed by the steam and water under the action of the heat of the fuel have been the cause of several vagaries of design, but the introduction of mechanical movement of the water will here also leave nothing to chance, and will ensure the realisation of the best conditions for working and for preservation of the boiler. It is not unlikely that, for the higher temperatures which must probably be faced in connection with steam generation, some adaptation of a film system, differing from that of Serpollet and that of Simpson and Bodman, will be combined with such forced circulation of the water. And if properly arranged, the division of the streams of hot gases also into thin films will no doubt be found advisable.

A survey of the many designs published in the past leads to the conclusion that there are in the main five distinct arrangements in water-tube designs which are practically possible, viz.,

first, vertical tubes; second, inclined tubes; third, coils; fourth, horizontal tubes, parallel coupling; and fifth, horizontal tubes, series coupling. There may be modifications of these, or combinations of one with another, but all boilers may be classed under these heads if the main features of design are taken into account, and we believe that we have here placed them in the distinct order of their value.

CHAPTER IX.

Some Tests of Boilers and Results.

It is obviously impossible within the limits of such a work as this to give a record of trials of all the boilers referred to in it. On this account a comparatively small number of such trials must be selected because of their possessing some features of special interest, either technical or historical. Some elements of comparison of different designs can be derived from such records, but a large number of details must be known before a complete or trustworthy comparison can be instituted between boilers differing widely in design.

The published proceedings of the Industrial Society of Mulhouse, and of the Royal Agricultural Society of England, contain valuable information regarding the testing of steam boilers of different types; and recent practice is shown in Donkin and Kennedy's "Tests of Steam Boilers"; "The Heat Efficiency of Steam Boilers," by Bryan Donkin; Professor Thurston's "Manual of Steam Boilers" (chap. xiv.), and in "The Marine Steam Engine," by Sennett and Oram (p. 85, etc.). Wm. Kent's "Steam Boiler Efficiency" should be studied in this connection, and reference should be made to the new standard tests of which some notice will be found in Min. Proc. Inst. C. E., Vols. cxli., p. 383, and cxlii., pp. 414–419.

Of late years controversy has raged between the advocates of the cylindrical or Scotch form of boiler and those who support the introduction and use of water-tube designs. Personal or vested interests have as usual imported some bitterness into such controversy and prevented the question being debated solely on its scientific merits, with consequent loss to all concerned. And it has frequently been forgotten that in very few cases are the records of tests or catalogues of results sufficiently full and ample to justify any final conclusion as to the comparative merits of the different designs. Moreover, it should be remembered that whilst it is unlikely that any great improvement in construction or working can now be introduced in the case of

the cylindrical boiler, in that of the water-tube boiler there is not only room for improvement but great likelihood that improved forms will be introduced as experience with this type becomes extended. It is sometimes urged that the possibilities of forced combustion with the cylindrical boiler have not yet been fully investigated; but, as we have seen in Chapter IV., etc., improvement in methods of combustion can apply with greater force and readiness to the water-tube than to the other design. It may be admitted that few, if any, of the water-tube *boilers* hitherto actually introduced could profit by a development of forced combustion, but, on the other hand, should improvement in methods of combustion be introduced, the water-tube *system* undoubtedly presents more flexibility of adaptation to new conditions than does its rival.

Regarding the utilisation of the heat of the fire gases, the degree to which that is possible with the different systems turns largely upon the question whether conducting these gases through tubes which are surrounded with water, or dispersing them amongst tubes which are filled with water, is the more efficient arrangement. There are, of course, good points in both, but the considerations advanced in the preceding chapters undoubtedly show that the latter offers the best prospect of a satisfactory result from the point of view of heat transmission efficiency. It is but fair to add that such a result as is here contemplated has not yet been realised from any boiler of whatever design hitherto introduced, although some water-tube boiler trials have shown a higher rate of evaporation per square foot of heating surface than has been obtained with cylindrical boilers.

Payne's Result.—A reference to what is, perhaps, the oldest evaporative result on record shows how very small an advance has been made in utilisation of heat during 150 years. John Payne, in describing his steam boiler to the Royal Society of England in 1747 (see Phil. Trans., 1747, page 828), announced that he had "rarefied" or turned into steam 90 gallons of water with 112 lbs. of coal. This having been an evaporative rate of 8·03 lbs. of water per lb. of coal, is not very far behind the best results obtained to-day.

Mulhouse Trials.—Amongst the results given in the "Bulletin de la Société Industrielle de Mulhouse" (Vol. xliii., 1873) there

are the following comparative results obtained in 1872 in trials with *Cornish*, *Lancashire*, and *French*, or "Elephant" forms of boilers :—

TABLE LXVI.

	Cornish.	Lancashire	French.
Coal per hour ... ... lbs.	216	244	387
„ sq. ft. of grate ... ... „	15	13·2	14·4
Water per lb. of coal ... ... „	7·66	7·80	7·28
„ „ combustible ... ... „	8·89	8·99	8·20

Later comparative trials of *Lancashire*, *Fairbairn*, and *French* forms of boilers, published by the same society,[1] also yield interesting results, as do the experiments carried out by Mr. Isherwood[2] on a marine boiler with proportions of fire-grate and heating surface varied at will.

Isherwood's Trials.—From our point of view in this volume, however, more practical information is yielded by the trials of a *horizontal flue tube* and a *vertical water-tube* boiler (the latter being, however, only a tank boiler with vertical water-tubes inserted in a large flue) on board the U.S. steamer "San Jacinto." The grate area (108 sq. ft.) was the same in both boilers, and the ratio of grate area to heating surface was 1 to $24\frac{2}{3}$ in the flue boiler and 1 to $30\frac{1}{2}$ in the water-tube boiler.

The water-tube arrangement showed more rapid evaporation and more efficient heat utilisation than the other form. The following are the results with normal condition of heating surface in both boilers. They show that the water-tube arrangement evaporated 10·3 per cent. more water per hour and 18·8 per cent. more per pound of coal, and showed a temperature of waste gases fully 100° lower, than in the flue-tube arrangement.

[1] See also "The Steam Engine," by D. K. Clark, Vol. i., pp. 213-231.

[2] Experimental Researches in Steam Engineering. New York. 1865. Vol. ii.

TABLE LXVII.

	Natural Draught.		Forced Draught.	
	Flue tube.	Water tube	Flue tube.	Water tube
Coal per sq. ft. of grate per hour ...	12·6 lbs.	11·7 lbs.	24·5 lbs.	23·7 lbs.
Ash per cent.	14·3	16·8	14·8	16·3
Water at 212° evaporated per hour ...	12055lbs.	13301lbs.	17425lbs.	18564lbs.
„ „ „ „ lb. of coal	8·87 lbs.	10·54 lbs.	6·57 lbs.	7·26 lbs.
„ „ „ „ combustible	10·35 lbs.	12·67 lbs.	6·92 lbs.	8·68 lbs.
Temperature in uptake	462° F.	356° F.	...	...
Air pressure at blower	...	...	1·54 ins.	1·54 ins.

Similar results, but on a more elaborate scale, are shown in the following tables recording further trials of two marine donkey boilers in the U.S. Navy Yard, New York; one of these boilers having an ordinary horizontal fire-tube, and the other having vertical water-tubes on Martin's plan, as in the "San Jacinto's" boilers.

Although Martin's boiler was not a true water-tube boiler, but was only a tank boiler fitted with vertical water-tubes in the large horizontal return flue, yet in these trials it showed a higher evaporative efficiency than did the other with horizontal return flue tubes.

This result can have been due only to the superior efficiency of the water-tube heating surface, as the total quantity of fuel consumed and of water evaporated in a given time was greater in the case of the flue-tube boiler.

TABLE LXVIII.

HORIZONTAL FLUE-TUBE BOILERS *versus* VERTICAL WATER-TUBE BOILERS OF THE "DONKEY" CLASS, U.S.N. 1865, 1866.

Furnace door-holes, except for No. 2 trial, closed. Anthracite coal. Steam of atmospheric pressure.

Reference No.	Conditions.	Temperature of Air	Temperature of Feed.	HORIZONTAL FLUE-TUBES. Coal Consumed. Coal. Per Hour.	Coal. Per ho. per sq. ft. of Grate.	Refuse.	Combustible. Per Hour.	Combustible. Per sq. ft. of Grate.	Water Evaporated. Per Hour.	Per sq. ft. of Grate.	From and at 212° F. Per pound of Coal.	From and at 212° F. Per pound Combust'le.	Temperature in Uptake	VERTICAL WATER-TUBES. Coal Consumed. Coal. Per Hour	Coal. Per ho. per sq. ft. of Grate.	Refuse.	Combustible. Per Hour.	Combustible. Per sq. ft. of Grate.	Water Evaporated. Per Hour.	Per sq. ft. of Grate.	From and at 212° F. Per pound of Coal.	From and at 212° F. Per pound Combust'le.	Temperature in Uptake.
		Fahr.	Fahr.	lbs.	lbs.	p.cent	lbs.	lbs.	cu. ft.	cu. ft.	lbs.	lbs.	Fahr.	lbs.	lbs.	p.cent	lbs.	lbs.	cu. ft.	cu. ft.	lbs.	lbs.	Fahr.
	1. PRELIMINARY: *Furnace Door-holes Open versus Closed.*																						
1	Door-holes open	30°.1	37°.7	889	24.70	20.0	711	19.75	91.04	2.53	7.54	9.48	—	613	15.72	21.7	480	12.31	79.04	2.03	9.49	12.13	—
2	Door-holes closed	33 .1	39 .5	894	24.84	21.3	703	19.54	91.09	2.53	7.49	9.52	—	647	16.59	23.6	494	12.66	79.81	2.05	9.77	11.88	459°
	2. DIMINISHING FIRE-GRATES.																						
1	Boiler as built	30°.1	37° 7	889	24.70	20.0	711	19.75	91.04	2.53	7.54	9.48	—	613	15.72	21.7	480	12.31	79.04	2.03	9.49	12.13	—
1 *a*	Grates 6 feet long, 36 square feet	52 .7	42 .0	792	22.01	23.2	608	16.90	88.80	2.47	8.22	10.71	—	541	15.04	23.5	414	11.51	69.41	1.93	9.41	12.29	339°
1 *b*	Do. 5 ft. long, 30 sq. ft.	44 .7	46 .8	683	22.75	21.7	535	17.82	78.96	2.63	8.45	10.79	lead melts	485	15.31	24.3	348	11.61	62.05	2.07	9.85	13.01	320
1 *c*	Do. 4 ,, 24 ,,	46 .6	48 .0	544	22.67	22.0	424	17.68	66.97	2.79	8.98	11.52	,,	381	15.99	23.9	292	12.17	54.21	2.26	10.31	13.55	287
1 *d*	Do. 3 ,, 18 ,,	46 .8	49 .6	445	24.74	22.8	344	19.10	54.37	3.02	8.90	11.52	570°	305	16.95	25.3	228	12.66	41.54	2.31	9.92	13 20	264
1 *e*	Do. 2½ ,, 13.5 ,,	63 .8	53 .9	323	23.90	20.4	257	19.02	39.87	2.95	8.97	11.27	478	211	15.64	23.1	162	12.02	28.70	2.13	9.86	12.84	286
	3. DIMINISHING GRATES. *10 lbs. Coal per hour per square foot of Grate.*																						
3	Grates as built	34°.7	40°.0	609	16.90	22.3	473	13.13	73.95	2.05	8.93	11.50	—	608	15.57	23.9	462	11.84	75.36	1.93	9.12	11.99	409°
3 *a*	Do. 36 square feet	53 .1	45 .7	370	10.27	23.6	282	7.84	48.75	1.35	9.51	12.45	512°	369	10.25	22.9	285	7.92	51.64	1.43	10.22	13.26	324
3 *b*	Do. 30 ,,	47 .5	48 .0	320	10.66	18.8	259	8.65	43.40	1.45	9.90	12.20	510	320	10.66	19.3	258	8.60	47.15	1.57	10.75	13.33	294
3 *c*	Do. 24 ,,	54 .0	49 .4	250	10.41	16.3	209	8.71	33.42	1.39	9.75	11.65	431	250	10.41	17.0	207	8.64	36.15	1.51	10.55	12.70	266
3 *d*	Do. 18 ,,	53 .1	50 2	190	10.58	26.3	152	8.43	25.62	1.42	9.79	12.29	399	148	10.56	21.7	149	8.27	27.45	1.52	10.52	13.44	242
3 *e*	Do. 13.5 ,,	59 .4	54 .0	142	10.54	23.3	109	8.08	18.84	1.39	9.61	12.53	360	143	10.55	24.2	108	8.00	20.52	1.52	10.45	13.79	232
	4. EQUAL COALS CONSUMED.																						
9	Grates 6 feet long	73°.4	69°.3	700	19.45	19.3	565	15.68	83.74	2.33	8.55	10.60	lead melts	700	19.42	22.0	545	15.15	83.94	2.33	8.58	11.00	447°
9 *bis*	—	68 .0	75 .0	799	22.19	17.0	663	18.43	97.51	2.71	8.67	10.44	lead and zinc melt	793	22,03	16.7	661	18.36	98.96	2.75	8.87	10.64	lead melts
	5. FLUEWAY AND HEATING SURFACE REDUCED BY PLUGGING TUBES.																						
No. 3	Boiler as built	34°.7	40°.0	609	16.90	22.3	473	13.13	73.95	2.05	8.93	11.50	—	—	—	—	—	—	—	—	—	—	—
1866. Oct. 31	2 upper rows plugged	43 .0	57 .8	633	17.57	20.2	505	14.03	80.92	2.25	9.25	11.58	lead melts	—	—	—	—	—	—	—	—	—	—
Nov. 7	3 ,, ,,	50 .3	57 .0	595	16.52	18.9	482	13.40	77.79	2.16	9.46	11.67	,,	—	—	—	—	—	—	—	—	—	—
,, 12	4 ,, ,,	43 .8	56 .0	527	14.65	21.0	417	11.57	73.44	2.04	10.09	12.77	,,	—	—	—	—	—	—	—	—	—	—
,, 21	5 ,, ,,	41 .5	53 .2	496	13.78	18.6	403	11.21	65.62	1.82	9.61	11.81	,,	—	—	—	—	—	—	—	—	—	—
,, 26	6 ,, ,,	39 .9	48 .0	394	10.96	21.4	310	8.62	52.21	1.45	9.66	12.28	,,	—	—	—	—	—	—	—	—	—	—
,, 29	7 ,, ,,	43 .0	51 .0	261	7.24	19.6	210	5.82	35.65	.99	9.95	12.38	498°.6	—	—	—	—	—	—	—	—	—	—
Dec. 5	8 ,, ,,	46 .8	51 .1	111	3.09	21.3	88	2.43	16.35	.45	10.70	13.60	383	—	—	—	—	—	—	—	—	—	—
1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	16	17	18	19	20	21	22	23	24

TABLE LXIX.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1866.	6. FLUEWAY REDUCED BY FERULES.																						
Dec. 10	Greatest closure above	21°.5	49°.5	630	17.49	19.4	507	14.09	81.56	2.27	9.44	11.72	between lead&zinc	—	—	—	—	—	—	—	—	—	—
„ 12	Greatest closure below	21 .5	47 .1	673	18.71	18.9	546	15.18	86.37	2.40	9.37	11.55	lead melts	—	—	—	—	—	—	—	—	—	—
„ 17	Closure uniform	30 .3	45 .0	638	17.75	18.7	519	14.42	83.35	2.31	9.55	11.75	„	—	—	—	—	—	—	—	—	—	—
	7. WATER-TUBES REMOVED. *Natural Draught.*																						
No. 3	Boiler as built	34°.7	40°.0	—	—	—	—	—	—	—	—	—	—	608	15.57	23.9	462	11.84	75.36	1.93	9.12	11.99	409°.0
1867.																							
Oct. 16	3 cross rows removed	57 .1	63 .0	—	—	—	—	—	—	—	—	—	—	552	14.15	17.2	457	11.72	78.50	2.01	10.04	12.16	415 .9
„ 30	6 „ „ ...	53 .5	60 .9	—	—	—	—	—	—	—	—	—	—	597	15.32	17.8	491	12.58	86.00	2.21	10.37	12.63	421 .4
Nov. 7	9 „ „ ...	51 .7	58 .0	—	—	—	—	—	—	—	—	—	—	611	15.67	16.6	509	13.06	84.91	2.18	10.04	12.05	491 .2
„ 18	12 „ „ ...	25 .3	54 .0	—	—	—	—	—	—	—	—	—	—	679	17.40	16.3	568	14.55	92.08	2.36	9.85	11.77	600 .0
„ 25	15 „ „ ...	48 .8	51 .0	—	—	—	—	—	—	—	—	—	—	651	16.69	16.5	543	13.93	87.27	2.24	9.76	11.69	between lead&zinc
Dec. 4	18 „ „ ...	27 .5	48 .2	—	—	—	—	—	—	—	—	—	—	760	19.49	18.5	619	15.88	95.08	2.44	9.13	11.20	„
„ 12	21 „ „ ...	26 .3	43 .6	—	—	—	—	—	—	—	—	—	—	762	19.54	16.5	636	16.31	92.81	2.38	8.92	10.69	zinc melts
	8. WATER-TUBES REMOVED. *Coal 12 lbs. per square foot of Fire-grate per hour.*																						
Oct. 14	3 cross rows removed	55°.9	63°.1	—	—	—	—	—	—	—	—	—	—	463	11.93	15.1	393	10.08	71.81	1.84	11.20	13.20	—
„ 28	6 „ „ ...	55 .2	60 .9	—	—	—	—	—	—	—	—	—	—	463	11.88	15.5	392	10.04	70.06	1.80	10.89	12.89	—
Nov. 5	9 „ „ ...	40 .2	59 .0	—	—	—	—	—	—	—	—	—	—	465	11.92	13.8	401	10.28	70.42	1.81	10.94	12.68	—
„ 13	12 „ „ ...	39 .1	56 .6	—	—	—	—	—	—	—	—	—	—	462	11.86	14.5	395	10.14	68.25	1.75	10.68	12.50	—
„ 21	15 „ „ ...	43 .0	51 .6	—	—	—	—	—	—	—	—	—	—	469	12.02	14.2	402	10.31	66.83	1.71	10.37	12.08	—
Dec. 2	18 „ „ ...	32 .2	49 .7	—	—	—	—	—	—	—	—	—	—	468	12.01	13.7	404	10.37	67.64	1.73	10.52	12.19	—
„ 10	21 „ „ ...	26 .0	46 .0	—	—	—	—	—	—	—	—	—	—	470	12.06	15.8	396	10.15	63.02	1.62	9.90	11.64	—
„ 18	24 „ „ ...	17 .5	40 .0	—	—	—	—	—	—	—	—	—	—	469	12.02	16.0	394	10.10	60.12	1.54	9.59	11.41	—
	9. TUBES CUT OFF FLASH-FLUE.																						
No. 23	—	73°.3	69°.5	831	23.10	19.3	671	18.63	55.05	1.53	4.73	5.86	—	821	21.05	19.5	661	16.95	56.75	1.46	4.94	6.13	—
No. 22	—	59 .3	65 .2	602	16.73	17.9	494	13.73	47.44	1.32	5.65	6.89	—	603	15.46	17.8	495	12.70	48.54	1.24	5.78	7.03	—
No. 24	—	63 .8	67 .4	311	8.65	17.0	259	7.88	29.75	.83	6.84	8.24	—	312	8.00	16.3	261	6.70	29.66	.76	6.81	8.13	—
	10. AUGMENTED COMBUSTION.																						
S 6	Jet in chimneys..........	40°.8	40°.0	962	26.71	16.3	805	22.37	109.59	2.81	8.38	10.00	zinc melts	802	20.57	18.2	656	16.83	105.01	2.70	9.62	11.76	488°.4
S 7	Air forced into ashpits.	50 .2	50 .2	957	26.58	18.5	780	21.67	105.60	2.71	8.05	9.88	„	956	24.52	18.2	782	20.06	105.05	2.70	8.02	9.80	lead and zinc melt
S 8	Do. do. grates 6 feet.	48 .0	48 .0	951	26.43	17.7	783	21.76	99.86	2.56	7.62	9.25	„	947	26.30	17.7	779	21.65	99.22	2.76	7.60	9.23	„
I 7	Do. do. „ 6½ ft.	49 .0	54 .0	—	—	—	—	—	—	—	—	—	—	1263	32.38	16.8	1050	26.93	103.85	2.66	5.97	7.17	zinc melts
	11. EXTREMES OF COMBUSTION.																						
I 7	Forced maximum.......	49°.0	54°.0	—	—	—	—	—	—	—	—	—	—	1263	32.38	16.8	1050	26.93	103.85	2.66	5.97	7.17	zinc melts
I 8	5 lbs. coal per sq. foot of grate per hour...	49 .0	54 .0	—	—	—	—	—	—	—	—	—	—	189	4.85	12.1	166	4.27	33.00	.85	12.63	14.37	199°
I 10	10 lbs. do. do.	84 .0	75 .0	—	—	—	—	—	—	—	—	—	—	383	9.83	20.8	304	7.7[illegible]	63.50	1.63	11.76	14.86	322 .4

S.S. "Thetis."—Of boilers of the water-tube or sectional class proper we have many records of trials and performances.

In 1858 a marine boiler of the *Craddock* design (with the addition of a steam dome and some slight alteration in the furnaces and passages for gases, steam and water), having nine square feet of heating surface per lb. of coal consumed per hour, gave in the s.s. "Thetis" results which showed an evaporation of 11 lbs. of water per lb. of coal, which had a theoretical evaporative power of $15\frac{1}{2}$, as certified by the late Professor Macquorn Rankine.

As a mean of 226 indicated horse power per hour was developed on a consumption of 1·018 lb. coal per I.H.P., the boiler cannot, however, have had a very active evaporation from each square foot of heating surface. The steam pressure in the boiler was 115 lbs. per square inch.

Similar results at pressures from 120 to 150 lbs. per square inch were obtained with sectional and water-tube boilers of Rowan and Horton's design, during the period from 1859 to 1874,[1] but the time was not then ripe for the employment in marine practice of those higher pressures of steam which make this class of boiler almost a necessity, and the use of water-tube marine boilers was all but discontinued in this country for some years.

On land, however, many different forms of water-tube boilers have been systematically tested during that period.

American Trials.—At the Fair of the American Institute in November, 1871, some careful tests were carried out by a committee presided over by Professor R. H. Thurston, who published the results in a paper read before the American Society of Engineers.[2] The water-tube boilers tested were those of *Root*, *Allen*, and *Phleger*, and along with these were tried a *Lowe* boiler and a *Blanchard* boiler, both being modifications of the flue-tube boiler.

The results are given in the following table :—

[1] See Trans Inst. Engineers and Shipbuilders in Scotland. Vol. xxiii., pp. 51-78, and Vol. xli., pp. 29-143.

[2] See *Engineering*, 15th January, 1875, pp. 49, 50. Also "The Steam Engine," by D. K. Clark, Vol. i., pp. 248-252.

TABLE LXX.

RESULTS OF THE COMPETITIVE TRIAL OF STEAM BOILERS AT THE FAIR OF THE AMERICAN INSTITUTE, NOVEMBER, 1871.

Name.	Square feet.		Ratio of Heating Surface to Grate Surface.	Total Weights.					Ratio of Water Primed to Water Evaporated.	Mean Temperature.						
	Grate Surface.	Heating Surface.		Coal.	Combustible.	Feed.	Steam.	Primed Water.		Injection.	Feed.	Water of Condensation.	Discharge.	Steam.	Super heat.	Flues.
	A.	B.	C.	D.	E.	F.	G.	H.	I.	J.	K.	L.	M.	N.	O.	P.
Root	27	876½	32·5	3,800	3,185·5	27,896	27,896	0·	0·	45·94°	45·94°	58·31°	143·1°	334·6°	16·08°	416·6°
Allen	32¼	920	28·5	5,375	4,527	39,670	39,670	0·	0·	45·5	45·5	63·48	154·76	330·63	13·23	345·87
Phleger ...	23	600	26·1	2,800	2,274	20,428	19,782·94	645·06	3·26	45·65	45·65	54·38	120·83	321·06	0·	503·76
Lowe	37¾	913	24·2	4,400	3,705	34,000	31,663·35	2,336·65	6·9	45·0	45·0	54·8	131·5	319·48	0·	389·6
Blanchard ...	8½	440	51·8	1,232	1,047·5	10,152·5	9,855·6	296·9	3·	44·4	44·4	49·49	106·14	323·75	0·	221·67

RESULTS, &c.—(*Continued*).

Name.	Total British Thermal Units.	Total Units per pound of Combustible.	Apparent Evaporation.				Actual Evaporation.		Equivalent Evaporation of Water at 212 deg. Fahr. and Atmospheric Pressure.	Square feet of Heating Surface required to evaporate one cubic foot of Water per hour.	Coal, pounds per square foot Grate Surface per hour.	Efficiency; Actual evaporation of Fuel divided by Theoretical.
			Per pound of Coal.	Per pound of Combustible.	Per square foot of Grate Surface per hour.	Per square foot of heating Surface per hour.	Per pound of Coal.	Per pound of Combustible.				
	Q.	R.	S.	T.	U.	V.	W.	X.	Y.	Z.	Z 1.	Z 2.
Root	32,751,834·34	10,281·53	7·34	8·76	86·09	2·65	7·34	8·76	10·64	23·59	11·73	0·709
Allen	46,387,827·1	10,246·92	7·38	8·76	102·51	3·59	7·38	8·76	10·60	17·41	13·88	0·707
Phleger ...	23,066,685·39	10,143·66	7·26	8·95	73·70	2·83	7·07	8·70	10·49	22·74	10·13	0·699
Lowe	37,228,739·072	10,048·24	7·68	9·12	75·06	3·10	7·20	8·55	10·40	21·63	9·71	0·693
Blanchard ...	11,485,777·35	10,964·94	8·24	9·69	99·53	1·92	8·00	9·41	11·34	33·48	12·10	0·756

These tests possess additional interest from their being amongst the first in which estimations of the dryness of the steam or amount of priming water present were made by the calorimetric method. For the particulars of the method adopted and of the calculations and formulæ employed, Professor Thurston's paper must be consulted.[1]

Howard Boilers.—The record of experiments on "Howard" inclined tube boilers, carried out by a Committee at the Fair of the American Institute in 1874, will be found in *Engineering* of January 26th, March 2nd, and April 13th, 1877, pages 80, 176, and 226 of Vol. xxiii. It has also features of great interest. The following is an abstract of the principal results :—

	1st.	2nd.	Mean.
Duration of experiments	10·5	11	
Pounds of fuel fed into furnace ...			5,100
" " coal and ashes withdrawn			1,158
" " combustible consumed...			3,942
" " water fed into boiler ...	17,338	21,015	37,403[2]
Less priming water...	452	3,100	3,552
Pounds of water evaporated ...	16,886	17,915	33,851[2]
Pressure of steam in boiler ...	76·5	138·3	
Temperature of feed	35°	36°	
" " atmosphere ...	35°	45°	
" " steam in drum ...	314°	346·8°	(by thermometer.)
" " gas leaving boiler	332°	324·2°	
" " " entering chimney		234°	
Pounds of combustible per hour ...			183·5
" " " " sq. foot of grate			6·8
" " " " " " heating surface			0·308
Apparent evaporation per lb. of combustible	9·024	9·915	9·469[2]
Effective	8·798	8·368	8·543
" from 212°	10·75	10·28	10·53
Percentage of total absorption (useful)	·742	·709	·726

[1] See also *Engineering*, Vol. xiii., 1872, pp. 340, 373, 377, 434.

[2] There is apparently some slight error in these figures, as the totals of the water do not agree in themselves or with the rate of evaporation.

At the conclusion of the experiment, with the steam pressure at 75 lb., the safety valve was closed, and the steam allowed to accumulate in the boiler until the pressure reached 135 lb.

During the interval the fires were burning at the same rate as during the other parts of the experiment.

The following Table shows the increase of pressure :—

TABLE LXXI.

Time.	Steam.	Time.	Steam.
hrs. min.		hrs. min.	
5 30	79	5 49	115
5 43	90	5 50	118
5 44	93	5 51	122
5 45	100	5 52	125
5 46	103	5 53	131
5 47	105	5 54	135
5 48	110	5 55	blow off.

The boiler had been fed with cold water just before 5.30, and it is believed that the temperature of the water in the boiler was not uniform until 5.43, after which the increments of temperature appear to be nearly uniform, being $2\frac{1}{10}$ deg. per minute.

The weight of water in the boiler was 4,400 lb., and the equivalent weight of iron surrounding it was 1,200 lb., giving the total equivalent weight of water to be elevated in temperature to be 5,600 lb. The increase of the temperature of the water was from 5·43 to 5·54, being 11 min. (358·45—331·18=) 27·25 deg. The units of heat corresponding to this elevation of the temperature of the whole mass would be (27·25×5600=) 178300.

This amount of heat was transferred in 11 min. The amount transferred during one hour, at this rate, would have been (178300÷11×60=) 861800 units, corresponding to (861800÷1156=) 741 lb. of steam from the temperature of the feed.

But during the interval immediately succeeding the elevation of temperature, the boiler was evaporating (183·5×8·8=) 1615 lb. of steam per hour. If this rate of transfer had continued during the elevation of temperature the increment would have been (2·1×1615÷741=) 4·4 deg. per min. So far as this experiment goes, it would appear that the heat was only transferred about one-half as fast while the pressure was rising as while it was uniform.[1]

If the heat should be transferred during the whole time while the pressure was rising to that pressure at which the boiler would burst, at the same rate as during the elevation of pressure between the two experiments, the bursting pressure would be reached in nearly 23 min., for the bursting pressure of the tube is 3000 lb., and the temperature corresponding to 3000 lb. in 797 deg.,

[1] Heat and Steam Engine. Trowbridge, p. 106.

and (797—320÷2·1=) 22¾ min. This is about half as long a period as would usually be occupied by the ordinary forms of boiler. The rapid variation of pressure is the result of the small weight of water contained in the boiler. This is an important feature of all the boilers of the class to which this belongs. It must be remembered that the cast-iron heads will probably give out at a less pressure than 3000 lb., although the Committee have no means of determining at what pressure they will give out.

It will be observed that the temperature of the gas leaving the boiler is less than the temperature of the steam due to the pressure. Under these circumstances, no super-heating is possible with any super-heater whatever. It will also be observed that at one time the temperature of the gas leaving the boiler is considerably hotter than the temperature due to the pressure of the steam, but the temperature indicated by the thermometer on the steam drum is less than the equivalent temperature of the steam. The following Table exhibits this variation :—

TABLE LXXII.

Hour.	Pressure.	Measured Temperature of Steam.	Equivalent Temperature of Steam.	Temperature of Gas.	Differences.	
					Gas and Equivalent Temperature of Steam.	8 Temperature and Measured Temperature.
9·30	72	319	317·3	350	+32·7	+ 1·7
10·00	73	311·5	318·2	375	56·8	— 6·7
10·30	78	311·5	322·2	400	77·8	—10·7
11·00	74	311·5	319	415	94·0	— 7·5
11·30	76	310·5	320·6	390	69·4	—10·1
12·00	75	310	319·8	390	70·2	— 9·8
12·30	80	316	323·6	380	56·4	— 7·0
1·00	80	320	323·6	350	26·4	— 3·6
1·30	77	311	321·4	330	8·6 (+57·8)	—10·4 (—8·)
2·00	80	319	323·6	310	—22·6	— 4·6
2·30	70	307	315·8	320	+ 4·2	— 8·8
3·00	75	312	319·8	315	— 4·8	— 7·8
3·30	79	318	322·9	310	—12·9	— 4·9
4·00	75	312	319·8	310	— 9·8	— 7·8
4·30	84	·318	326·6	315	+11·6	— 8·6
5·00	73	310·5	318·5	315	— 3·5	— 8·0
5·30	79	315	322·9	310	—12·9—(10)	— 7·9 (7·64)

The strength of the tubes of this boiler being $8\frac{3}{8}$ in. inside diameter, and $\frac{5}{16}$ in. thick, taking the strength of the iron at 50,000 lb., and the welded joint at 20 per cent. less, will be

$$\left(\frac{\cdot 80\times 50{,}000}{8\frac{3}{8}}\times\frac{5}{8}\right) = 3000 \text{ lb. nearly per sq. in.}$$

The cast-iron heads are probably not so strong as the tubes, but the Committee have no means of determining how strong they are.

If it is true, as said by an eminent engineer, that "in nine cases out of ten a continuously increasing pressure of steam without means of escape, is the immediate cause of explosion,"[1] the liability to explosion would decrease as the margin of strength increases, and this must be looked upon as a very strong and safe boiler.

There is another point, however, which the Committee do not feel justified in passing without comment. The feed water is introduced into all the lower rows of tubes from a common pipe, and these tubes are only connected with the steam space by the back end. Now, it is evident that if there is any steam formed in the lower tubes, it must leave them by the back end, and that there would be a constant current of steam leaving the tubes, tending to carry the water with it. It is no doubt the expectation of the builder that there will not be any steam formed in the lower tubes, but that they will only serve as a feed water heater, and that the cold water pumped in at a lower end will be gradually forced along the tube by the fresh supply of water coming on behind it, becoming warmer and warmer as it travels along the tube, but not reaching the temperature of the steam until it arrives at the end and mixes with the water circulating through the upper tubes. So long as this is the case, no harm can come from having these tubes connected at one end only. The effective surface of the lower row of tubes being one-half the total surface, 50 square feet is equal to ($\frac{50}{27}$=) 1·85 time the grate surface. From experiments with other boilers, at the same rate of combustion, it appears that about 6000 units of heat would be absorbed by this surface for every pound of combustible consumed. During the experiment, the feed water had a temperature of 35 deg., and each pound of combustible elevated 9 lb. of water from the temperature of the feed to the steam, and evaporated 8·8 lb., the balance, 2 lbs., being entrained with the steam. Thus the total heat absorbed was :

Water	$9\times 286=2574$
Steam	$8{\cdot}8\times 888=7814$
	10388

Therefore the units of heat available to form steam in the lower tube (6000 —2574=) 3426, and the equivalent weight of steam (3426÷888=) 3·86. That is (3·86÷8.8=) 44 per cent. of the total steam formed in the boiler will be formed in the lower tubes. If the water received heat uniformly from the time of its entrance during its passage along the tube, it would have acquired

[1] Sir William Fairbairn—Useful Information for Engineers. 1st Series, p. 58, Ed. 1864.

the temperature of the steam at (2791÷6000×12=) 5·6 ft. from the front end of the tube, at this point the steam would commence to form and the current of water would be reversed. If the combustion is slow, as in the experiment, these two currents may pass each other without interference, but if the combustion be sufficiently rapid so that more heat is thrown on the lower tube (see Fig. 309), or if the feed water enters the tube at a higher temperature than 35 deg., so much steam may be formed that the opposing currents of steam and water will interfere and drive the water from the tube, when the tube would soon become red hot, and burst with a very moderate pressure. Although it is not probable that there would be an explosion in the ordinary acceptation of the term, still the steam and water would pour out into the furnace with certainly disastrous and perhaps fatal results. Your Committee cannot say at what rate of combustion or temperature of feed steam would be formed in the lower tubes with sufficient rapidity to expel the water. That can only be determined by experiment, but they refer to the performance of a similar boiler, the boilers of the steamship "Montana," which would seem to corroborate these views.[1] In the form of boiler at present manufactured by the exhibitors, the tubes are connected at both ends, which would obviate this trouble.

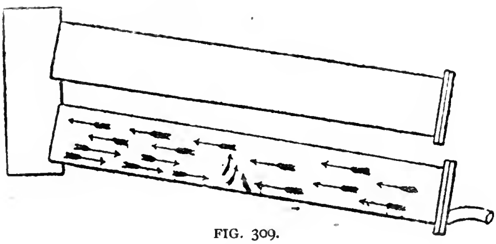


FIG. 309.

If there were consumed in this boiler ½ lb. of combustible for every square foot of heating surface per hour, the percentage of perfect absorption would be, computed as in the other cases, 62·4 per cent.

In comparing this boiler experiment with those made under atmospheric pressure, and the ordinary temperature (60 deg.), an allowance should be made for the greater proportion of the heat necessarily rejected through the chimney, for the gas must at best be discharged at the temperature of the steam, if there is no feed water heater.

This allowance will be for the Howard boiler under these circumstances of the trial[(335−35)÷(212−60)=] nearly 2; the heat necessarily wasted in the ordinary atmospheric test, which is [(212−60)÷(2240−60)=] 6·8 per cent., and therefore in the Howard boiler (2×6·8=) 13·6 per cent.

That is, if the Howard boiler had been tried under atmospheric pressure, and with an atmospheric temperature of 60 deg., the percentage of heat use fully absorbed would have increased from 62.4 to (62.4+6.8=) 69.2.

The same reasoning applies to the boilers tested at the Fair in 1871."

[1] *Nautical Magazine*, London, November, 1873.

The log of the Allen boiler is here added for comparison.

CALCULATION OF THE LOG OF THE ALLEN BOILER, EXHIBITED AT THE FAIR OF THE AMERICAN INSTITUTE, NOVEMBER, 1871.

Determination of the heat carried away by the condensing water discharged from the tank during the twelve hours' trial :—

	Units.
To 1.30 p.m., 1056 cubic ft. at $62\frac{1}{2}$ lb.=66,000 lb. at range of 120·7° F.	7,966,200
To 10.30 p.m., 5480 cubic ft. at $62\frac{1}{2}$ lb.=342,500 lb. at range of 106·08° F.	36,332,400
To 11·35 p.m., 650 cubic ft. at $62\frac{1}{2}$ lb.=40,625 lb. range of 50·5° F.	2,051,562·5
(*a*) Total British thermal units	46,350,162·5

Determination of heat carried off by evaporation at the surface of the tank :—

	Units.
1168·12 lb. × 1008·8° (latent heat at 152·7° F.)=(*b*)	1,178,404·5

Determination of heat carried away by water of condensation :—

	Units.
39,670 lb. at 17·98° (range=63·48°—45·5°)=(*c*)	713,266·6

Total heat derived from fuel, as determined above :—

	Thermal units.
46,350,162·5+1,178,404·5+713,266·6=	48,241,833
Deduct 4 per cent. of (*a*) for errors (leakage, and meters) ...	1,854,006·5
Final and corrected results	46,387,827·1

British thermal units per lb. combustible, 46,387,827·1÷4527=10,246·92.

Equivalent evaporation of water, temperature 212° F., atmosphere pressure =10,246·92÷966·6=10·60 lb.

	Apparent results.	Real results.
Water evaporated per lb. of coal	$\frac{39670}{5375}=7·38$	$\frac{39670}{5375}=7·38$
Water evaporated per pound of combustible ...	$\frac{39670}{4527}=8·76$	$\frac{39670}{4527}=8·76$

TABLE LXXIII.—LOG OF TRIAL OF ALLEN'S STEAM BOILER, NOVEMBER 14th. 1871.

Time.	Barometer.	Steam.	Weight		Temperatures.						Reading of Meters.			
			Coal.	Feed.	Injection and feed.	Steam.	Water of condensation.	Discharge.	Flues.	Atmosphere.	Feed.	Injection. 1.	2.	3.
A.M.					Deg.	Deg.	Deg.	Deg.	Deg.	Deg.				
10.30	30·05	...	400	...	45·5	...	...	...	...	46·	14308·			
11	30·05	68·	400	300	45·5	316·	50·5	...	220·	46·	14311·	29244	6290	
11.30	30·02	73·	600	900	45·5	325·	58·5	145·5	245·	48·	14323·5	29293	6353	
12	30·00	71·	0	1500	45·5	330·	65·	158·	250·	46·	14347·2	29406	6486	
P.M.														
12.30	29·98	72·	200	2100	45·5	330·	71·	169·5	255·	47·	14377·7	29502	6600	
1	29·95	70·	200	1800	45·5	328·	74·	178·	260·	47·	14313·0	29622	6714	
1.30	29·92	74·	0	1800	45·5	336·	77·5	180·	265·	48·	14441·5	29730	6860	25
2	29·90	69·	200	1800	45·5	328·	83·	180·	265·	48·	14470·0	29815	6981	80
2.30	29·90	72·	200	900	45·5	334·	65·	172·	...	48·	14498·8	29910	7099	154
3	29·86	64·	200	1800	45·5	330·	66·5	164·	405·	48·	14528·2	30028	7234	237
3.30	29·86	67·	400	1500	45·5	336·	57·	145·	410·	48·	14550·1	30123	7352	313
4	29·85	65·	200	1800	45·5	328·	61·	153·	400·	48·	14576·8	30225	7468	385
4.30	29·84	75·	200	1800	45·5	336·	60·	148·	390·	49·	14604·4	30334	7601	466
5	29·82	71·	200	1500	45·5	330·	60·5	148·5	380·	42·	14632·1	30421	7713	537
5.30	29·80	69·	200	1800	45·5	332·	59·	148·	370·	50·	14659·0	30544	7851	622
6	29·77	67·	200	1500	45·5	330·	59·	147·	375·	50·	14685·6	30641	7973	696
6.30	29·74	70·	400	1500	45·5	330·	57·5	141·	370·	50·	14710·5	30756	8092	771
7	29·72	67·	0	2100	45·5	328·	61·	147·	390·	52·	14736·2	30854	8215	854
7.30	29·72	70·	200	1500	45·5	330·	59·5	150·	390·	52·	14764·3	30985	8342	927
8	29·70	75·	400	1800	45·5	336·	60·	143·	375·	51·	14789·5	31067	8476	1010
8.30	29·70	75·	200	1800	45·5	338·	62·5	145·	390·	52·	14816·5	31172	8597	1085
9	29·68	76·	200	2100	45·5	336·	67·	151·	400·	52·	14844·8	31272	8722	1162
9.30	29·64	78·	175	1200	45·5	328·	62·5	150·	380·	52·	14873·9	31379	8847	1240
10	29·64	70·	0	2100	45·5	332·	66·	149·	400·	52·	14899·8	31486	8973	1319
10.30	29·62	75·	0	1500	45·5	328·	60·	147·	370·	52·	14928·5	31596	9101	1398

REMARKS.—Trial commenced at 10.46 A.M. Pounds of wood, 400; pounds of ashes, 848. Temperatures of discharge, taken at frequent intervals, from 10.46 A.M. up to 11·35 P.M. 146. 144½. 140. 135. 124. 103, 88, 77, 66, 6 , 57, 54, 52 deg. Final reading of meters at 11·35 P.M.; feed, 14943·5; injection No. 1, 31767·5; injection No. 2 9393; injection No. 3, 1584·5; pounds of feed from 10.30 P.M. to 11.35 P.M., 1270.

Philadelphia Exhibition, 1876.—Of similar interest and importance are the records of tests of various boilers which were carried out at the Centennial Exhibition at Philadelphia in 1876, and at the Electrical Exhibition held in the same place in 1884.

The following Table gives a summary of the principal dimensions of the various boilers tested in 1876 :—

Table LXXV.

Philadelphia Exhibition, 1876,—Surfaces and Volumes of Steam Boilers Tested, mostly Sectional.

Designation of Boiler.	Area of Fire-grate.	Heating Surface.			Ratio of Water-heating Surface to Grate-area.	Volume of Boiler.		
		Water.	Steam.	Total.		Water-space.	Steam-space.	Total.
	sq. feet.	sq. feet.	sq. feet.	sq. feet.	ratio.	cu. feet.	cu. feet.	cu. feet.
Wiegand	42	1289.70	49.67	1339.37	30.7	181.36	44.18	225.54
Harrison	23	627	274	901	27.3	54.09	23.72	77.81
Firmenich	15.41	1001.10	30	1031.10	64.3	145.12	92.20	237.32
Rogers and Black	21	—	—	399.75	19.0	36.15	24.85	61.00
Andrews	18.42	288.04	218.36	506.40	15.6	80.74	25.45	106.19
Root	42	1451.77	146.66	1598.43	34.6	116.68	45.69	162.37
Kelly (including ⅓ of water-heater)	27.50	575.06	60.48	635.54	20.9	58.17	27.97	86.14
Exeter	30	1005.06	557.94	1563	33.5	83.77	44.60	128.37
Lowe	22.50	687.88	65.76	753.64	30.6	140.18	50.90	191.08
Babcock and Wilcox	44.50	1676.32	—	1676.32	37.7	229	137.85	366.85
Smith	25	1146.43	7.57	1154	45.8	136.12	127.39	263.51
Galloway	36	852.54	—	852.54	23.7	562.91	169.12	732.03
Anderson	36	630	485.	1115	17.5	66.90	55.75	122.65
Pierce	25	—	—	349.33	14.0	20.11	43.11	63.22

The results obtained in these trials have been published with some slight variations by the makers of certain of the boilers, but the following Table gives those accepted by the late D. K. Clark as an impartial judge in the matter :—

TABLE 75A.

PHILADELPHIA EXHIBITION, 1876.—CAPACITY TRIALS (OR TRIALS FOR EVAPORATIVE POWER) OF STEAM BOILERS—MOSTLY SECTIONAL.

Fuel, Anthracite. Effective Pressure of Steam, 70 lbs, per square inch. Duration of Trial, 8 Hours.

DESIGNATION OF BOILER....		Wiegand.	Harrison.	Firmenich.	Rogers & Black.	Andrews.	Root.	Kelly.	Exeter.	Lowe.	Babcock & Wilcox.	Smith.	Galloway.	Galloway, bituminous coal.	Anderson.	Pierce.
1. Coal consumed per hour, including equivalent of wood	pounds.	670.8	413.7	233.2	266.9	229.4	543.3	449.5	411.3	237.3	675.9	398.8	462.5	410.7	524.0	258.9
2. Coal consumed per hour per sq. ft. of fire-grate..	"	16.0	17.9	15.1	12.7	12.4	12.9	16.4	13.7	10.5	15.2	15.9	12.8	11.4	14.6	10.4
3. Refuse per hour	"	56.9	35.6	20.1	21.0	21.6	52.5	39.0	38.1	25.2	53.0	37.2	51.1	39.1	46.5	21.8
4. Do. per cent	p. cent.	8.5	8.2	8.6	8.0	9.4	9.7	8.7	9.3	10.7	7.8	9.3	11.6	9.5	8.7	8.5
5. Combustible per hour	pounds.	613.9	378.1	213.1	245.9	207.7	490.8	410.5	373.2	212.1	622.9	361.6	411.3	371.6	478.5	237.1
6. Do. do. per sq. foot of fire-grate	"	14.6	16.4	13.8	11.7	11.3	11.7	14.9	12.4	9.4	14.0	14.5	11.4	10.3	13.3	9.5
7. Temper. of feed-water	Fahr.°	74.1	71.3	68.9	65.8	66.5	63.7	61.3	60.5	60.2	57.6	58.2	56.0	54.0	54.7	52.2
8. Water consumed per hr., apparently evaporated	cu. feet.	76.98	51.80	31.76	30.58	26.80	67.49	56.92	52.56	31.92	87.07	57.63	61.36	58.00	61.41	33.61
9. Water evaporated per hour, corrected for quality of steam	"	76.47	50.80	31.97	31.35	27.40	69.17	46.40	50.11	32.13	86.39	57.93	61.86	57.72	61.31	31.25
10. Do. do. do. per square foot of fire-grate	"	1.82	2.21	2.08	1.49	1.49	1.65	1.69	1.67	1.43	1.94	2.32	1.72	1.60	1.70	1.25
11. Do. per pound of coal	pounds.	7.11	7.66	8.55	7.33	7.45	7.94	6.44	7.60	8.45	7.98	9.06	8.35	8.77	7.28	7.53
12. Do. per pound of coal, from and at 212° F.	"	8.39	9.03	10.09	8.65	8.75	9.45	7.66	9.04	10.06	9.50	10.78	9.94	10.44	8.66	8.96
13. Do. per pound of combustible	"	7.77	8.38	9.36	7.96	8.23	8.79	7.06	8.38	9.48	8.66	10.00	9.38	9.69	7.97	8.22
14. Do. do. from and at 212° F.	"	9.14	9.89	11.06	9.43	9.74	10.44	8.40	9.97	11.16	10.33	11.92	11.22	11.61	9.57	9.86
15. Priming, or moisture in steam	p. cent.	.81	2.07	—	—	—	—	18.6	4.8	—	.94	—	—	.62	.31	7.1
16. Superheating of steam	degs. F.	—	—	9.1	43.9	39.1	43.6	—	—	9.9	—	6.4	11.7	—	—	—
17. Temperature of burnt gases leaving the boiler	Fahr.°	605	584	418	649	383	—	—	438	360	473	435	322	383	534	456

These trials are arranged under the two heads of "capacity" and "economy"; "capacity" being taken as the quantity of water evaporated per hour or evaporative power, and "economy"

TABLE 75B.

PHILADELPHIA EXHIBITION, 1876.—ECONOMY TRIALS (OR TRIALS FOR EVAPORATIVE EFFICIENCY) OF STEAM BOILERS—MOSTLY SECTIONAL.

Fuel, Anthracite. Effective Pressure of Steam, 70 lbs. per square inch. Duration of Trial, 8 Hours.

DESIGNATION OF BOILER.		Wiegand.	Harrison.	Firmenich.	Rogers & Black.	Andrews.	Root.	Kelly.	Exeter.	Lowe.	Babcock & Wilcox.	Smith.	Galloway.	Galloway, bituminous coal.	Anderson.	Pierce.
1. Coal consumed per hour, including equivalent of wood......................	pounds.	518.9	284.4	185.3	181.7	148.2	381.7	297.6	280.6	153.1	444.4	303.7	346.0	283.5	350.9	199.9
2. Coal consumed per hour per sq. ft. of fire-grate..	"	12.3	12.4	12.0	8.6	8.0	9.1	10.8	9.3	6.8	10.0	12.1	9.6	7.9	9.7	8.0
3. Refuse per hour...........	"	49.3	24.2	19.2	17.9	15.3	40.0	26.8	32.0	17.3	48.8	33.8	38.5	25.0	32.5	22.0
4. Do. per cent...........	p. cent.	9.5	8.5	10.4	9.9	10.3	10.4	9.0	11.4	11.3	11.0	11.1	11.1	8.8	9.3	11.0
5. Combustible per hour...	pounds.	469.6	260.2	166.1	163.8	132.9	341.7	270.8	248.6	135.8	395.6	269.9	307.5	258.5	318.4	177.9
6. Do. do. per sq. foot of fire-grate..................	"	11.2	11.3	10.8	7.8	7.2	8.1	9.8	8.3	6.0	8.9	10.8	8.5	7.2	8.8	7.1
7. Temper. of feed-water....	Fahr.°	70.8	71.2	68.9	67.1	65.4	64.6	66.9	68.9	66.4	64.0	61.8	56.0	55.1	54.0	53.2
8. Water consumed per hr., apparently evaporated	cu. feet.	68.29	38.93	26.50	21.75	19.07	54.53	40.00	35.13	21.77	64.76	43.80	47.63	42.04	44.80	25.13
9. Water evaporated per hour, corrected for quality of steam.........	"	69.10	38.62	27.00	21.33	19.84	55.83	37.80	33.72	21.91	63.14	43.30	47.74	41.99	45.25	23.85
10. Do. do. do. per square foot of fire-grate.........	"	1.65	1.68	1.75	1.01	1.08	1.33	1.38	1.16	.97	1.42	1.73	1.33	1.17	1.26	.95
11. Do. per pound of coal...	pounds.	8.31	8.47	9.09	7.33	8.35	9.13	7.93	7.50	8.93	8.87	8.93	8.61	9.24	8.07	7.44
12. Do. per pound of coal, from and at 212° F.....	"	9.81	9.99	10.73	8.65	9.85	10.77	9.36	8.85	10.63	10.56	10.63	10.25	11.00	9.60	8.85
13. Do. per pound of combustible..................	"	9.18	9.26	10.14	8.13	9.31	10.20	8.81	8.46	10.07	9.96	10.01	9.69	10.13	8.87	8.36
14. Do. do. from and at 212° F.....................	"	10.83	10.93	11.99	9.61	11.04	12.09	10.31	10.04	11.92	11.82	11.91	11.58	12.12	10.62	10.02
15. Priming, or moisture in steam......................	p. cent.	—	.93	—	2.14	—	—	5.59	4.16	—	2.67	1.31	---	.28	—	5.24
16. Superheating of steam...	degs. F.	20.5	—	32.6	—	71.7	41.3	—	—	9.45	—	—	1.41	—	15.7	—
17. Temperature of burnt gases leaving the boiler	Fahr.°	524	518	415	572	420	393	—	430	332	296	411	303	325	417	374

as quantity of water evaporated per pound of fuel under ordinary working conditions. A comparative view of the performances of these various boilers is afforded by Table LXXVI. :—

TABLE LXXVI.

PHILADELPHIA EXHIBITION, 1876.—COMPARATIVE PERFORMANCES OF STEAM BOILERS OF DIFFERENT KINDS.

Designation of Boilers.	Capacity Trials.		Economy Trials.		Heating Surface per sq. foot of fire-grate.		Features of Boilers.
	Water per pound of combustible from and at 212 F°.	Combustible per sq. foot of fire-grate.	Water per pound of combustible from and at 212° F.	Combustible per sq. foot of fire-grate.	Water.	Steam.	
1	2	3	4	5	6	7	8
	pounds.	pounds.	pounds.	pounds.	sq. feet.	sq. feet.	
Smith	11.92	14.5	11.91	10.8	45.8	·3	Cylindrical shell, multitubular flue—water-tubes in side flues; underfiring.
Galloway	11.22	11.4	11.58	8.5	23.7	—	Cylindrical shell, furnace tubes and water-tubes.
Lowe	11.16	9.4	11.92	6.0	30.6	3.0	Cylindrical shell, multitubular flue; underfire.
Firmenich	11.06	13.8	11.99	10.8	64.3	2.0	3-inch water-tubes, nearly vertical; reversed draught.
Root	10.44	11.7	12.09	8.1	34.6	3.5	4-inch water-tubes, inclined 20° to horizontal; reversed draught.
Babcock & Wilcox	10.33	14.0	11.82	8.9	37.7	—	3½-inch water-tubes, inclined 15° to horizontal; reversed draught.
Exeter	9.97	12.4	10.04	8.3	33.5	18.6	27 hollow rectangular cast-iron slabs.
Harrison	9.89	16.4	10.93	11.3	27.3	12.0	8 slabs of cast-iron spheres, 8 inches in diameter; reversed draught.
Pierce	9.86	9.5	10.02	7.1	14.0	?	Rotating horizontal cylinder, with flue-tubes.
Andrews	9.74	11.3	11.04	7.2	15.6	12.0	Square fire-box and double return multitubular flues.
Anderson	9.57	13.3	10.62	8.8	17.5	14.0	3-inch flue-tubes, nearly horizontal; return circulation.
Rogers & Black	9.43	11.7	9.61	7.8	19.0	?	Vertical cylindrical boiler, with external water-tubes.
Wiegand	9.14	14.6	10.83	11.2	30.7	1.2	4-inch water-tubes, vertical, with internal circulating tubes.
Kelly	8.40	14.9	10.31	9.8	20.9	2.2	3-inch water-tubes, slightly inclined; each divided by internal diaphragm to promote circulation.

Some figures enabling a comparison to be made between these and the Howard boilers already referred to, will be found in *Engineering*, Vol. xxiii., p. 176.

The following diagram, Fig. 310 (published in the 1884 edition of *Steam* by the Babcock and Wilcox Company) exhibits the effects of comparing these various boiler trials in respect of several elements :—

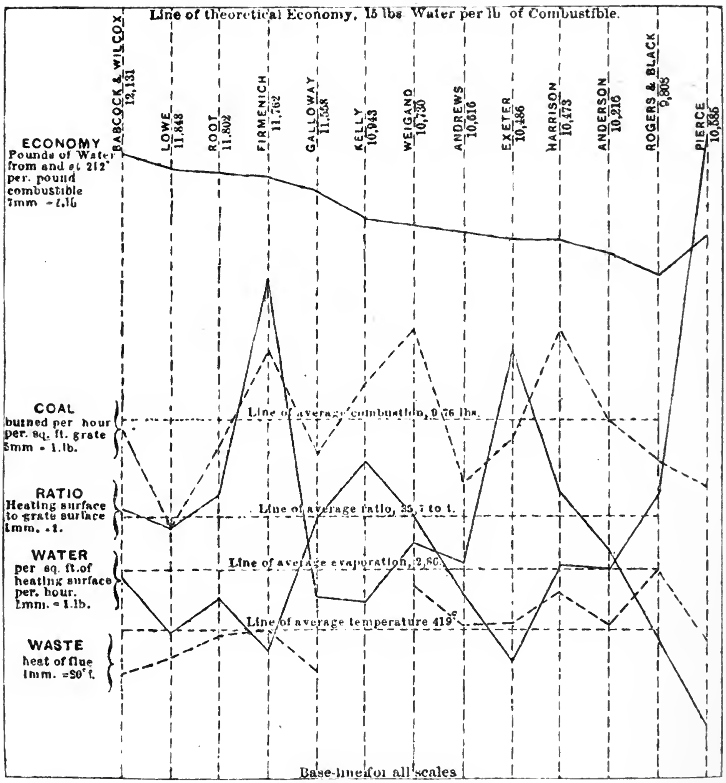


FIG. 310.

The following remarks accompanied this diagram :—

"Entirely independent of the question, which boiler is the best for use? there is an inquiry of great interest in a scientific point of view, and that is What elements in the construction or arrangement of the boilers tested contributed to the difference in results? Not enough data are given to enable us to solve this problem; but to show what, if any, effect certain elements produced, we have constructed the annexed diagram. The height of the diagram is 15 centimeters, and represents the *theoretic value* of the combustible

used in the experiments. In the line of "economy" the boilers are arranged in the order of their relative economy, as shown in the Table. The distance of this line from the base, relative to the whole height, gives the *percentage of useful effect* in each case, and it is the relation of the other lines to this that we have to study.

"If we examine the line representing the evaporation per square foot of surface, we are struck at once by the fact that it bears no relation whatever to the line of economy. Now, we know that in any given boiler, this frequently has a marked effect in that respect; other things being equal, the slower the rate of evaporation per square foot, within certain limits, the higher the economical results. But, as the value of the heating surface under differing arrangements varies in a much greater ratio than the effect of forcing a given surface, as our diagram shows, no general rule can be made to apply. The same remarks will apply to the lines representing the rate of combustion per square foot of grate, and the ratio of heating surface to grate surface. These latter must have a conjoined relation to the rate of evaporation, modified also by the quality of the heating surface; but for the same reason above given, no general relation exists between them and the economical effect in different boilers. To show this more perfectly, we have drawn an average line in each case (not including the very erratic results of the Pierce boiler, for reasons above given), and it will be seen thereby, that boilers at the extremes of economy had an average of each of these conditions. The different results are, therefore, to be attributed to difference in the construction of the boilers, by which the heating surface was rendered more effective. The fact that the best economic results were obtained by a boiler under average conditions in other respects, is significant, and shows that more is to be hoped for through improved construction and arrangement, than from extremes in proportion.

"The line representing the heat in flue, as was to be expected, bears a general ratio to the total losses, though not directly in each individual case. This line is probably too low in every case, as it undoubtedly is in several, where the temperature in the flue is given as lower than that of the steam, which could only result from the leakage of air into the flue. As it is not to be supposed that such an error could have been permitted, the discrepancy is probably chargeable to the pyrometer used."

It is, however, quite possible to read this diagram in another light.

Philadelphia Electrical Exhibition, 1884.—At the International Electrical Exhibition at Philadelphia in 1884, trials of two sectional or water-tube boilers, viz: the *Root* and the *Harrison*, and two shell or multitubular flue-tube boilers, viz: the *Dickson* and the *Baldwin*, were carried out.

Table LXXVII gives the principal dimensions of these boilers :—

TABLE LXXVII.—INTERNATIONAL ELECTRICAL EXHIBITION, 1884.—SURFACES AND VOLUMES OF STEAM BOILERS TESTED : SECTIONAL AND MULTITUBULAR.

Designation of Boiler.	Root.	Harrison.	Dickson.	Baldwin.
Nominal horse-power, rated by makers...H.P.	150	100	76	50
Water-heating surface......................sq. ft.	1440	948.5	841	663.3
Steam-heating surface...................... „	360	349	2.5	136.3
Total heating surface .... „	1800	1297.5	843.5	799.6
Grate-area.................................. „	50	35.13	31.41	21
Ratio of grate-area to heating surface.....	1 to 36	1 to 37	1 to 26.8	1 to 38
Heating surface per horse-power...........sq. ft.	12	13	11.1	16
Grate-area per horse-power................ „	.51	.35	.41	.42
Height of chimney above level of grate....feet	44.5	44.5	28.6	44.5
Steam-room in boiler ....cu. ft.	7.65	29.8	67	—

The principal results of the performance of these boilers are given in Table LXXVIII :—

TABLE LXXVIII.—INTERNATIONAL ELECTRICAL EXHIBITION, 1884 :— COMPARATIVE PERFORMANCE OF STEAM BOILERS.

Designation of Boiler.	Root.	Harrison.	Dickson.	Baldwin.
Duration of trial..................................hours	36	36	36	24
Coal consumed per hour, including equivalent of wood.................. .... pounds	502.5	328.0	558.0	253.2
Do. do. per sq. ft. of fire-grate. „	10.05	9.3	17.8	12.0
Refuse per hour.......................... .... „	74	41	140	27
Do. per cent.................................p. cent	14.7	12.5	25.0	10.7
Combustible per hour ....pounds	428.5	287.0	418.0	226.2
Do. do. per square foot of grate.......... .... „	8.6	8.2	13.3	10.8
Temperature of feed-water.......................Fahr.	71°.6	68°.8	67°.2	59°.9
Water evaporated per hour....................cub. ft.	60.06	41.22	61.06	25.45
Water evaporated per hour per sq. ft. of fire-grate.................................... „	1.20	1.17	1.94	1.21
Water evaporated per pound of coal.........pounds	7.45	7.84	6.83	6.27
Water evaporated per pound of coal, from and at 212° F. .... „	8.79	9.25	8.06	7.40
Water evaporated per pound of combustible.. „	8.75	8.96	9.12	7.02
Water evaporated per pound of combustible from and at 212° F.................. „	10.32	10.57	10.76	8.28
Priming, or moisture in steam.................p. cent	—	—	1.55	—
Superheating of steam.........................degs. F.	9°.4	2°.2	—	7°.0
Temperature of burnt gases in chimney......Fahr.	370°	411°	423°	347°
Effective steam-pressure per square inch......lbs.	91.4	95.8	83.5	98.7
Barometer....................................... inches	30.3	30.3	30.3	30.3
Draught in chimney........................... „	.7 blower	.24 natural	.15 steam jet	.43 natural
Temperature of the air................ .... Fahr.	7°	58°	50°	45°
Air consumed per pound of coal......... lbs.	22.29	20.06	18.74	20.24
Air consumed per pound of coal......... cub. ft. at 62° F.	293	264	246	266

Fletcher's Trials.—To conclude this survey of trials of land water-tube boilers, we add the results of comparative trials of a *Sinclair* boiler and a *Lancashire* boiler as carried out by Mr. Lavington E. Fletcher.[1] The Sinclair boiler was of 75 nominal horse power, and was composed of 115 water-tubes of 11ft. 9 ins. long and 4 inches diameter. The Lancashire boiler was 25ft. 3 ins. long, and 7 feet in diameter, with two furnace tubes 2 ft. 9 ins. in diameter. The respective areas were :

	Sinclair.	*Lancashire.*
Grate area	39·5 sq. ft.	36·6 sq. ft.
Heating surface	1507·0 „	698·5 „
Ratio of above	1 to 38·1 „	1 to 19·1 „

The boilers were fed with cold water, and the leading results were as follows :—

Table LXXIX.

Sinclair and Lancashire Boilers :—Comparative Trials.

Designation of Boiler.	Sinclair.	Lancashire.	Lancashire.
Duration of trial	7 hours	7 hours	4½ hours
Pressure of steam in boiler	30 lbs. to 35 lbs.	35 lbs. to 40 lbs.	30 lbs. to 35 lbs.
Coal consumed per hour	5.86 cwt. = 656 lbs.	7.57 cwt. = 848 lbs.	7.45 cwt. = 833.7 lbs.
Do. do. per sq. foot of grate	16.6 „	23.17 „	22.77 „
Temperature of feed-water	88°.8	80°.6	85°.2
Water evaporated per hour	75.90 cu. ft.	78.76 cu. ft.	78.20 cu. ft.
Do. do. per sq. foot of grate	1.92 „	2.15 „	2.14 „
Do. do. per pound of coal	7.23 lbs.	5.80 lbs.	5.86 lbs.
Do. do. from and at 212° F.	8.31 „	6.67 „	6.74 „
Temperature in flue, beyond damper	450° F.	800° and upwards	800° and upwards

Comparative Space Occupied.—A rough comparison of the space occupied by various types of land boilers is afforded by the following tabular statement, published by J. H. Ashby in a paper on water-tube boilers in Proc. Cleveland Inst. of Engineers (3rd October, 1898) :—

[1] See "*The Engineer*," 24 August, 1877, p. 129.
Reports of the Manchester Steam Users Association, November and December, 1877.
Also "The Steam Engine," by D. K. Clark, Vol. i, p. 274.

TABLE LXXX.

Type of boiler.	Sizes.	Space occupied over setting with combustion chamber.	Mean evaporation per hour.
Lancashire with three flues	36 ft. by 8 ft. 6in. diameter	46 ft. by 13ft.	8·00
Lancashire with two flues	30 ft. by 8 ft. diameter	40 ft. by 12 ft. 6 ins.	6·50
Egg-ended	60 ft. by 4ft. diameter	62 ft. by 8 ft.	2·50
Babcock and Wilcox	2852 sq. feet heating surface.	32 ft. by 10 ft. 10 ins.	13·00

Donkin's Experiments.—A summary of twenty-one experiments was published by Mr. Bryan Donkin in *Engineering* (20 Sept., 1895), Vol. lx. p. 347.

The following tables give particulars of the dimensions of the boilers, and of the results of the various trials.

TABLE LXXXI.

Date of Trials, 1887 to 1889	I	II.	III.	IV	V	VI.	VII.	VIII.	IX.	X.
Place of Test	B. Donkin and Co.'s Works, Bermondsey.			Engineering Laboratory, University College, London.		Liége, Belgium, Professor Dwelshauvers Dery.		East London Water Works, Bow	London Hydraulic Power Company	
Type of Boiler	Vertical Tubular Boiler with Internal Firebox.	Lancashire Conical, Tubes across each Flue.		Locomotive Type, with Wet Firebox.		Multitubular Boiler on De Naeyer's System.		Three Cornish Boilers, each with Three Cross Tubes in Flue.	Lancashire Boilers with Galloway Tubes in each Flue, Green's Economiser, Vicars' Mechanical Stokers.	
Heating surface { Boiler alone .. sq. ft.	771	582	582	228	228	470.5	470.5	2100	936	936
Heating surface { Economiser	none	none	none	none	none	470.5	470.5	none	1142	1142
Total heating surface	771	582	582	228	228	941.0	941.0	2100	2078	2078
Area of firegrate	10.5	15	15	10.5	7.4	14.95	14.95	63.0	21.0	21.0
Ratio $\frac{\text{Boiler surface}}{\text{Grate surface}}$ ..	73.4	38.8	38.8	21.7	30.8	31.5	31.5	33.3	44.6	44.6
Ratio $\frac{\text{Total heating surface}}{\text{Grate surface}}$ ..	73.4	38.8	38.8	21.7	30.8	63.0	63.0	33.3	99.0	99.0
See ENGINEERING for full details	July 18, 1890	August 1, 1890		November 21, 1890.		February 27, 1891.		May 15, 1891.	October 2, 1891.	
Direction of gases, &c.	Up through centre of boiler, down three flues outside of boiler, up three flues outside boiler to chimney. Flues brick.	Through two boiler tubes, along two sides brick flues, then under boiler to chimney.		No brick flue; straight through boiler.		Direct through boiler and economiser to chimney.		Through centre tube, split sides, under boiler, to chimney.	Through two tubes, under bottom of boiler, split two sides to chimney.	
Type of boiler	Vertical Tubular	Lancash.		Loco. Type		Water Tube		Cornish	Lancash.	

Date of Trials, 1887 to 1889	XI.	XII.	XIII.	XIV	XV	XVI.	XVII	XVIII.	XIX.	XX.	XXI
Place of Test	B. Donkin and Co.'s Works, Bermondsey	Scheurer-Kestner, Thann, Alsace	Great-Eastern Railway Works, Stratford.	Stratford to Lynn	Lynn to Stratford	Merryweather and Son's Works, Greenwich.	Bedford Press, ENGINEERING	Royal Arsenal, Woolwich.	Central Institution of the City and Guilds, South Kensington.	Office of *Daily Telegraph.*	Royal Testing Station, Brussels.
Type of Boiler	Portable Boiler, Locomotive Type.	Elephant, with Green's Economiser, the latter generally used with Two Boilers.	Steel Locomotive Boilers of Tank Goode Engine, with Copper Firebox. Not Running.	Steel Locomotive Boilers of Tank Goode Engine, with Copper Firebox. Running.	Steel Locomotive Boilers of Tank Goode Engine, with Copper Firebox. Running.	Merryweather and Son's Patent Fire Engine, Vertical Multitubular Boiler.	Cornish Multitubular.	Portable Boiler, Locomotive Type.	Cornish, with Galloway Tubes.	Cornish Multitubular Boiler, Corrugated Flue.	Locomotive (Stationary).
Heating surface { Boiler alone .. sq. ft.	316	430	859	859	859	120	191.5	285	324	804	1177
Heating surface { Economiser	none	1033	none	none	none	none	none	none	none	none	none
Total heating surface	316	1463	859	859	859	120	191.5	285	324	804	1177
Area of firegrate	9.68	19.15	12.4	12.4	12.4	5.76	3.55	10.5	16.75	20 0	31.43
Ratio $\frac{\text{Boiler surface}}{\text{Grate surface}}$ ..	32.6	23.5	69.2	69.2	69.2	45.0	54.0	27.2	19.3	40.2	37.4
Ratio $\frac{\text{Total heating surface}}{\text{Grate surface}}$ ..	32.6	76 4	69.2	69.2	69.2	48 0	54.0	27.2	19.3	40.2	37.4
See ENGINEERING for full details	March 18, 1892	July 22, 1892	October 21, 1892			Jan. 27 189?	June 30, 1893	Dec. 22, 1893	June 15, 1894	July 20, 1894	Nov. 2, 1894.
Direction of gases, &c.	Direct through tubes up chimney.	Under three boiler tubes round upper boiler to economiser	No brickwork. Direct through boiler to chimney			Straight through boiler to chimney No brickwork.	Through tubes, then under boiler to chimney.	No brickwork. Straight through small tubes.	Through tube, then split sides and back under boiler.	Through tube, then under bottom then split two sides to chimney.	No brickwork. Through small tubes.
Type of boiler	Loco. Type	Elephant	Locomotive			Cross Tube Fire Engine	Cornish Multitubl.	Loco. Type	Cornish	Cornish Multitubr.	Loco. Type

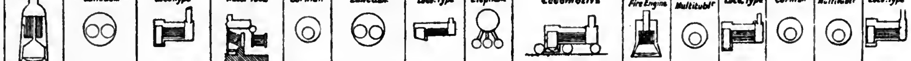


TABLE LXXXII.

Experiment Number..	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.	XXI.
1. Duration .. .. hours	8.5	9.0	12.0	6.83	6.0	6.6	9.05	10.0	9.0	9.1	8.0	31.8	8.31	4.88	4.76	6.0	9.0	5.3	8.0	7.0	5.0
2. Mean steam pressure absolute .. .. lb.	49.7	64.7	71.7	14.9	99.9	100.6	90.2	51.7	93.8	92.7	75.7	60.2	145.0	133.7	139.7	115.1	79.2	86.7	66.3	88.7	104.7
3. Corresponding temperature .. .. deg. Fahr.	280.6	297.5	304.4	212.7	327.7	328.5	320.5	283.0	323.1	322.4	308.2	292.8	355.6	349.3	352.7	338.0	311.3	317.7	299.1	319.3	331.0
4. Feed temperature .. .. .. ,,	42.6	48.6	71.1	42.0	86.0	49.1	40.3	110.2	83.5	86.8	56.3	65.3	56.5	50.7	52.0	52.0	58.7	60.0	96.1	47.5	59.2
5. ,, ,, after economiser .. ,,	..	..	..	..	..	204.2	205.3	..	226.3	202.0	..	225.0	..	..	..	..	159.0	..	..	163.0	
6. Total feed water evaporated .. .. .. lb.	12,975	11,497	28,427	4620	2009	13,374	18,215	44,010	31,969	34,220	8700	66,737	37,010	17,588	19,011	7861	3995	4869	16,331	28,141	35,492
7. ,, ,, ,, per hour.. .. ,,	1505	1277	2369	676	335	2026	1917	4401	3552	3760	1087	2100	4454	3620	4000	1310	444	920	2104	4020	7098
8. Total coal put on grate.. .. .. .. ,,	1660	1525	3374.5	607.5	309.5	..	..	4623	..	..	..	..	..	..	..	1249	449	616	2157	3084	4085
9. ,, drawn .. .. ,,	62.5	137.5	42.0	38.5	31.2	..	..	301	..	..	..	..	..	..	..	63.0	11.0	10.0	57.0	76.0	81.5
10. ,, used, including ash and clinker.. ,,	1597.5	1387.5	3332.5	569.0	278.3	1412	1990	4322	3017	3200	960	6720	3663	1701	1571	1156	438	606	2100	3008	4003
11. Total coal used, including ash and clinker, per hour .. .. lb.	188.0	154.0	278.0	83.3	46.3	214.0	220.0	432.0	336.0	352.0	120.0	211.5	441.0	348.0	393.0	197.6	48.7	114.0	262.5	429.6	801
12. Total weight of ash and clinker { ash .. ,,	55.5	76.5	54.5	43.2	15.3	58.2	57.5	315	19.0	22.4	10.0	463	168	64.5	78.0	14.0	1.0	26.0	117.5	54.5	209
clinker ,,	29.0	21.0	73.0	5.7	0 0			86	80.0	44.8	13.0		42	28.5	26.0	10.0	6.0	15.0	25.5	40.5	
13. Total percentage of total coal used .. { ash ..	3.5	5.5	1.6	7.6	5.5	4.1	2.9	7.3	0.6	0.7	1.04	6.9	4.58	3.8	4.2	1.2	0.2	4.3	5.6	1.8	5.2
clinker	1.8	1.5	2.2	1.0	0 0			2.0	2.6	1 4	1.35		1.14	1.7	1.4	0.8	1.4	2.5	1.2	1.3	
14. Percentage of moisture in fuel	1.6	5.5	4.2	about 1.0	0.4	1.26	1.26	0.35	1.95	2.35	1.8	0.8	0.6	about 0.5	about 0.5	about 1.0	0.26	about 2.0	1.09	1.15	1.5
15. Total weight of pure and dry coal used per hour lb.	175	135	256	75.2	43.6	202 5	211	390	318	336	115	195	413	327	369	192	47.8	104	242	412	747
16. Ratio to total coal used per hour	0.931	0.875	0.920	0.904	0.941	0.946	0.958	0.903	0.947	0.956	0.958	0.923	0.937	0.940	0.939	0.970	0.981	0.912	0.921	0.957	0 932
17. Thickness of fires .. .. in.	13to15	8.5	6.0	5 to 6	..	3.6	3.5	9 to 12	10to12	..	4.5	..	5 to 6	4 to 5	..	..	4	..	8	3 to 4	2½
18. Number of times each fire stoked per hour ..	2.1	1.2	2.75	0.88	..	12	12	0.7	conti	nuous	3.73	8.0	3	5	5.3	..	2.2	..	..	6	8
19. Temperature of air in boiler-house deg. Fahr.	57.5	65 5	69 0	53.0	78.0	42.8	42.8	78.4	98.0	51.0	59.0	79.3	61.2	48.5	55.5	..	67.5	..	73.2	86.4	55
20. ,, outside boiler-house ,,	32.0	34.8	64.0	46.0	..	42.8	42.8	45.1	42.5	39.0	59.0	68.2	61.2	48.5	55.5	45.2	..	..	53.1	47.0	55
21. Temperature of furnace gases at or near base of chimney .. .. deg. Fahr.	392	399	630	560	555	329	324	485	372	278	625	264	–	570	617	..	498	575	533	732	
22. Temperature between boiler and economiser deg. Fahr.	..	..	..	..	..	646	626	..	566	401											
23. Coal per hour necessary to maintain pressure only .. .. lb.	8.5	10.8	16.7	6.2	6.2	1[illegible]9	9.2	In each boiler 6.37	24.1	24.1	9.3	9.6	17.0	17.0	17.0	..	4.0	..	..	..	30
24. Coal per hour in percentage of total coal used per hour .. .. per cent.	4.5	7.0	6.0	7.4	13.4	6 5	4.2	4.4	7.2	6.0	7 75	4.5	3.85	4.9	4.3	..	8.2	..	..	..	3.7

Table LXXXIII.

ANALYSES OF AND CALCULATIONS CONNECTED WITH FURNACE GASES, &c.

Experiment Number ..	I.		II.		III.		IV.		V.		VI.		VII.		V.	
Analysis of Dry Furnace Gases.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.
1. Percentage of CO_2 } 100 p.c.	10.33	15.15	..	13.00	..	18.21		11.71	..	7.90	7.12	10.44	7.44	11.00	10.2[illegible]	14.[illegible]5
2. " CO	2.77	2.59	..	0 00	..	0.24	..	0.00	..	0.00	0.29	0.28	0.10	0 10	0.3[illegible]	[illegible].28
3. " O	6.07	6.46	..	11.16	..	7.65	..	13.13	..	17.00	12.61	13.37	12.34	13.20	7.80	[illegible]
4. " N	80.83	75.80	..	75.85	..	74.00	..	75.16	..	75.10	80 08	75.90	80.12	76.70	81.7[illegible]	76.46
5. Pounds of dry air per pound of C	18.5		27.6		19.2		30.7		46.0		33.1		32 3		23 3	
6. Pounds of dry air per pound of coal .. { line 5 × 0.886 }	16.4		24.4		17.0		27.2		40.7		29.3		28.6		2[illegible]	
7. Pounds of dry air per pound of pure and dry coal	16.9		25.2		17.5		28.0		42.2		30.3		29 3		2[illegible]	
8. Pounds of dry furnace gases ditto (not including H_2O)	17.6		25.8		18.1		28.6		42.8		30.9		30.2		21 [illegible]0	
9. Ratio of air used to air theoretically required	1.18		2.40		1.63		2.61		4.28		2 82		2 75		1 [illegible]3	

Experiment Number ..	IX.		XI.		XII.		XIII.		XIV.		XVII.		XIX.		XX.	
Analysis of Dry Furnace Gases.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.	Volume.	Weight.
1. Percentage of CO_2 } 100 p.c.	5.77	8.60	11.34	16.60	10.30	15.10	12.40	17.94	11.20	14 90	7.60	11.10	..	11.53	13.00	18.88
2. " CO	0.00	0.00	0.23	0.21	0.00	0 00	1 10	1.02	0.00	0.00	0.00	0.00	..	0.10	0 37	0.34
3. " O	13.37	14.40	7 33	7.76	8.30	8.80	6 20	6 53	7.10	6 60	12.18	13.10	.	13.03	5.54	5.8[illegible]
4. " N	80.86	77.00	81.10	75.53	81.40	76 10	80.30	74 51	81.00	78 50	80.32	75 80	..	75.44	81 09	74 93
5. Pounds of dry air per pound of C .. .	42.1		21.2		23 7		18.2		24.0		32.7		31.2		18 3	
6. Pounds of dry air per pound of coal .. { line 5 × 0.886 }	37.3		18.8		21.0		16.1		21.3		29 0		27.6		16.2	
7. Pounds of dry air per pound of pure and dry coal	38.6		19.4		21.7		16.7		22.0		30.0		23 6		16.8	
8. Pounds of dry furnace gases ditto (not including H_2O)	39.2		20.0		22 3		17.3		22 6		30.6		29.2		17.4	
9. Ratio of air used to air theoretically required	3.6		1.81		2.01		1.56		2.06		2.50		2.67		1.56	

TABLE LXXXIV.—PRINCIPAL RESULTS: COAL AND WATER.

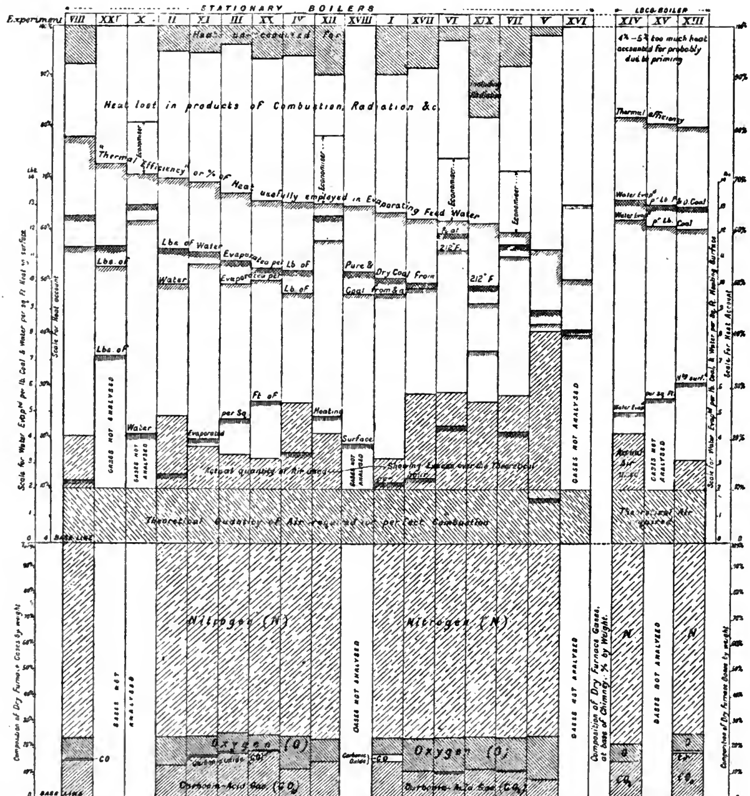
—	Experiment Number	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII	XIV.	XV.	XVI.	XVII	XVIII.	XIX.	XX.	XXI.
Coal ..	Combustion: 1. Pounds of coal burned per square foot of grate per hour	17.90	10.20	18.50	7.93	6.25	14.[illegible]	14.70	6.86	16.00	16.80	12.40	11.44	35.50	28.10	31.70	34.30	13.70	10.[illegible]0	15.70	21.[illegible]0	25.[illegible]0
	2. Pounds of coal burned per square foot of heating surface (boiler only) .. lb.	0.24	0.265	0.48	0.336	0.[illegible]03	0.466	0.469	0.206	0.359	0.376	0.350	0.490	0.514	0.406	0.458	1.650	0.254	0.400	0.310	0.534	0 6 0
	3. Pounds of coal burned per square foot of total heating surface with economiser	..	..	..	..	.	0.227	0.234		0.162	0.170	.	0.[illegible]45									
Thermal Units.	Transmission of heat: 4. Thermal units per square foot of heating surface per hour (boiler only) . ..	2250	2530	4610	3350	1660	4340	4120	22[illegible]0	37[illegible]0	4060	3920	4720	6040	4930	5440	12,650	2440	3730	7160	5240	6068
Water ..	Evaporation: 5. Equivalent water evaporated per pound of coal from and at 212 deg. Fahr. lb.	9 67	9.92	10.02	9.55	8.45	11.25	11.080	11 40	12.40	12.46	10.78	11.70	12.18	12.51	12.29	7.96	9.91	9.57	9.16	10.15	10.64
	6. Equivalent water evaporated per pound of pure and dry coal from and at 212 deg. Fahr. .. .. .. lb.	10.28	11.34	10.90	10 67	8.99	12.00	11.57	12.61	13.12	13.06	11.25	12.65	13.00	13.30	13.10	8.20	10.10	10.50	9 95	10.[illegible]0	11.42
	7. Equivalent water evaporated per square foot of heating surface (boiler only) from and at 212 deg. Fahr. .. lb.	2.33	2.62	4.78	3.47	1.73	4.49	4.26	2.84	3.87	4.20	4.05	4.89	6.25	5.10	5.62	13.1	2.52	3.85	7.43	5.42	7.23

TABLE LXXXV.—HEAT ACCOUNTS PER POUND OF PURE AND DRY COAL IN PER CENT.

Experiment Number ..	I.	II.	III.	IV.	V.	VI.	VII.	VIII	IX.	X.	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.	XXI.
Percentage of heat expended in																					
1. Heating and evaporating water	63.6	70.4	67.6	66.2	56.8	economiser, 11.9 boiler, 62.5	11.7 60.1	78.3	12.0 69.5	9.7 71.3	69.8	13.0 65.5	80.7	82.6	81 3	61.0	62.7	65.2	61.8	65.8	73.2
2. Heating furnace gases	9.4	13.6	16.2	22.5	31.8	13.8	13.3	14.0	19 3	..	18.0	6.5	15.9	18.6	20.0	..	20.7	.	20.4	18 0	
3. Evaporating moisture in coal	0.1	0.4	0.4	0.1	0.0	0.1	0.1	0 0	0.1	..	0.1	0.0	0.0	0.0	0 0	..	0 0	..	0.1	0.1	
4. Radiation .. .	4.5	7.0	6.0	5.2	9.4	6.5	6.3	4.4	7.2	..	5.7	5.5	3.0	3.9	3.4	..	8.2	..	not meas'rd	8.0	3.7
5. Heat in fire drawn ..	0.1	0.3	0.4	0.2	0.4	0.0	0.0	0.2	0.0	..	0.0	0 0	0.0	0.0	0.0	..	0.1	..	0.1	0.1	
6. Evaporating water under grate	..	3.4	4.6																		
7. Lost by imperfect combustion	12.7	0.0	1.2	0.0	0-0	2.4	0.8	1.7	0.0	..	1.2	0.0	4.9	0.0	0.0	..	..	..	0.0 Including radiation	1.6	
8. Unaccounted for ..	9.4	4.9	3.6	5.8	1.6	2.8	7 7	1 4	..	19.0	5.2	9.5	..	..	..	..	8.3	..	17.6	6 4	23 1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	108.1	100.0	100 0	100.0	104.5	105.1	104.7	..	100.0	..	100.0	100.0	100.0
Loss by heating furnace gases, apart from action of economiser . ..	9.4	13.6	16.2	22.5	31.8	25.7	25.0	14.0	31.3	..	13.0	19.5	15.9	18.6	20 0	..	20.7	..	20.4	18.0	

These results were plotted in a diagram giving a graphic representation of them arranged in the order of the thermal efficiencies yielded by the trials. Three locomotive trials were, however, treated separately on account of the conclusion that some priming had taken place in their case.

The following Fig. 311 is a reproduction of the diagram :—



Experiment	VIII	XXI	X	II	XI	III	XX	IV	XII	XVIII	I	XVII	VI	XIX	VII	V	XVI		XIV	XV	XIII
Steam Pressure lbs. p. sq. in above atmosphere	37	90	78	60	61	57	70	0	45	72	35	64	86	68	75	86	100		119	125	130
Temp. of Escaping Gases at base of Chy. °Fahr	485°	Not taken	After boiler 6[illegible]° After Econ. 278°	339°	625°	630°	232°	560°	264°	676°	332°	438°	After boiler [illegible]° After Econ. 3[illegible]°	528°	After boiler [illegible]° After Econ. 3[illegible]°	556°	Not taken		570°	617°	Not taken
Chimney Draught, ins. of Water	0·47"	0·81"	0·60"	0·35"	0·20"	0·40"	0·75"	0·17"	Not Taken	0·25"	0·20"	0·28"	0·15"	0·62"	0·16"	0·16"	1·0"		1·07"	1·26"	1·03"
Coal per Sq. Ft. Grate per hour, lbs.	6·66	25 8	16·8	10·8	12 4	16·6	21·5	7·33	11 0	10·6	17 3	13 7	14·3	15·7	14·7	8·65	34·3		28·1	31·7	35·6
Type of Boiler	Cornish, East London Water Works	Loco Type, Brussels	Lancash., Hydraulic Power Co. London	Lancash., Bermondsey	Loco. Type, Bermondsey	Lancash., Bermondsey	Cornish Tubular, Fleet Street	Loco. Type, University College London	Elephant, Alsace	Loco. Type, Woolwich?	Vertical Tubular, Bermondsey	Cornish Multitubular, Engineering? London	Water Tube, Liege	Cornish, [illegible] Kensington?	Water Tube, Liege	Loco Type, University College	Cross tube & engine, Greenwich		Locomotive Running, London to Lynn		Stationary, Stratford
Chimney: Height from Grate, Ft.	180' 6"	21' 11"	88' 6"	66' 9"	34' 9"	66' 9"	160' 6"	45' 10"	98' 6"	34' 8"	58' 0"	53' 2"	43' 3"	120' 0"	43' 3"	46' 10"	7' 0"		10' 4"		
Chimney: Area at base, Sq. Ft.	66·6	3 2	25·0	16 0	1 23	16 0	7·3	0·33	22 2	1 23	16·0	3 0	5·4	20·2	5 4	0·35	8 66		1·08		
Chimney: Area at Top, Sq. Ft.	13 6	3 2	33·0	2·25	1 23	2·25	7·3	0 54	5·0	1·23	2 25	3·0	6·4	10·0	5·0	0 34	0·75		1·52		

FIG. 311.

Marine Boilers.—In the early days of the introduction of steam of high pressure, generated in sectional or water-tube boilers, into steamships, the performance of the boilers was not noted separately, the main point of observation having been the quantity of coal consumed for the power developed by both boilers and engines. Consequently there is only a meagre supply of details available in the case of the boilers which were used. Published details of the engines are much more complete.

Rowan and Horton Boilers.—Table LXXXVI contains some particulars of the working of *Rowan and Horton* boilers, of both cellular and water-tube designs, during a period from the year 1858 to 1874. Of some other examples no record whatever has been kept.

The S.S. "Actif," which was a dispatch boat of the French Navy, was fitted in 1869 with the early form of Belleville boilers, to replace those of Rowan and Horton, the original engines remaining.

The boiler of the S.S. "Thetis" was of Craddock's design, modified to some extent by Rowan and Horton; those of the other vessels, down to and including the S.S. "Actif," were of Rowan and Horton's cellular design, whilst those of the "Haco," "Propontis," "Nepaul," and "Bengal," were of the Rowan and Horton water-tube form, as also were the second sets of boilers fitted in the steamers "Punjaub," "Oude," and "Burmah," in 1873-74. The cellular boilers were also fitted in the steamers "Progress" and "Ballina," and the S.S. "Western," these having been, like most of the others, constructed by Messrs. R. Stephenson and Co., of Newcastle-on-Tyne.

Although in all these steamers the power was produced with what was in those days a startling economy of fuel, and at a rate of combustion per I.H.P. not surpassed as yet, nevertheless the conditions of slow combustion under which the boilers were worked, made it necessary to have a large amount of heating surface, the unit of which consequently did not show a high evaporative efficiency.

TABLE LXXXVI.

ROWAN AND HORTON BOILERS.

	Name of Vessel.	Pressure of steam lbs. per sq. in.	Total heating surface sq. feet.	Grate area sq. feet	Consumpt'n of coal p. I.H.P. hour lbs.	Date of trials.
	S.S. Thetis	115	1923·15	36	1·01	Nov. 20, 1858.
	" "	90	—	—	1·20	Aug. 12, 1859.
	" "	—	—	—	1·70	Mean of 14 voyages, May 14 to Aug. 25, 1859.
	S.S. Queen of the Isles	98	880	19·44	1·74	Sept. 29, 1860.
	S. Guajara	102	2752	50	1·50	Jan. 15, 1861.
	S. Diamantina ...	111·5	1650	24	1·42	Jan. 22, 1861.
	" "	105	—	—	1·86	Coal includes laying fires April 17 to 26, 1862.
	" "	120	—	—	1·23	Jan. 30, 1861.
Sister Ships.	S.S. Sicilia	120			1·6	July, 1861.
	" "	115			1·36	Aug. 15, 1861.
	S.S. Italia	120	1135·6	48	1·5	Dec. 30, 1861.
Sister Ships.	S. Punjaub	120	3960	66		Mean of 22 trials, from June 13 to Aug. 30, 1861.
	S. Oude	120			1·7	
	S. Burmah	120				
	S.S. Actif	120	3740	62	1·6	Feb., 1862.
	S.S. Haco	150	1805·5		1·7	Oct., 1870.
	S.S. Propontis ...	131·4	8700	121·6	1·6	Mean of 63 observations, April 7 & 8, 1874.
	" "	132·9	—	—	1·64	Average of voyages, June 30 to July 16, 1874.

More Recent Trials.—The following Tables contain records of trials of various marine water-tube boilers of later date, and they explain themselves.

TABLE LXXXVII.—TRIALS OF MARINE WATER-TUBE BOILERS.

Published by Asst. Eng. S. H. Leonard, U.S.N., in Jour. Am. Soc. Nav. Eng., Vol. II., May, 1890.

Type.	Grate area.	Heating surface.	Ratio. $\frac{H.S.}{G.A.}$	Combustion per square foot of grate per hour	Evaporation from and at 212° Fah.				Per cent. moisture in steam.	Weights in lbs.					Air pressure, inches of water.	Steam pressure, lbs.	Coal.
					Per lb. coal.	Per lb. combustile.	Per square foot heating surface.	Per cubit foot space.		Empty.	Steaming level.	Per I.H.P.	Per square foot heating surface.	Per lb. water evaporation.			
Belleville	34·17	804	1 to 23·5	12·8	9·6	10·42	5·2	6·4	6·31	40,670	42,700	204	53·2	10·1	Natural draught	111	Bituminous
Herreshoff ...				9·3	7·6	10·23	3·1	9·1	3·5			96	14·8	4·8	Jet	120	Anthracite
	9	205.3	1 „ 22	25·8	7·14	8·68	8	23·8	...	2,945	3,050	36		1·8	Jet	195	„
Towne				4·3	10·46	13·4	2·7	10	...			172	21·8	8·1	Natural	148	Anthracite
	4.25	75	1 „ 17·6	24·5	5·6	6·77	8·2	30·4		1,380	1,640	56		2·6	1·14	152	„
Ward				7·9	8·59	10·77	1·7	5·8				154		7·7	Natural	0	Anthracite
(Launch Type) ...				15·5	8·28	10·01	3·2	11	...	1,682	1,930	82	13·2	4·07	Jet	17	„
	3·68	145·8	1 „ 39·5	62·5	6·34	7·01	10	36·2				26		1·3	Jet	161	Bituminous
Scotch				24·8	8·13	9·93	8·6	11	3·44			120	41·2	4·7	2·08	77	Anthracite
	31·16	727·2	1 „ 23·3	38	7·87	9·06	12·8	16·3	4·29	18,900	30,000	80		3·1	4·01	78	„
Locomotive				98·3	6·97	...	17·1	30·5	...	...	34,990	47·7	31·3	1·8	3·13	125	Bituminous
(Torpedo boat)	28	1116	1 „ 39·8	120·8	6·62		20·05	36·2				33·3		1·2	4·95	123	„
Ward	53	2473·5	1 „ 46·6	55·04	8·03	8·44	9·47	32·1	11·6	26,533	30,474	26	12·3	1·3	2	160	„
(Large type) ...	66·5	2490	1 „ 37·4														
Thornycroft U.S.S. "Cushing."	38·3	2375	1 „ 62	45	...	...	...	...	...	20,160	24 640	31	10·3	...	3	245	„

TABLE LXXXVIII.

Boilers in preceding Table with Thornycroft boiler of Torpedo boat "Ariete" added. Arranged by Engineer R. S. Giffen, U.S.N.

Boilers.	1	2	3	4	5
	Combustible per sq. feet of heating surface.	Evaporation per lb. combustible.	Heating surface per cubic foot.	Weight per sq. ft. heating surface.	$\frac{1\times2\times3}{4}$
Ward (Launch) ...	·159	10·77	3·413	13·2	·443
Towne ...	·190	13·40	3·694	21·8	·431
Herreshoff ...	·301	10·23	2·945	14·8	·613
Ward (Launch) ...	·323	10·01	3·413	13·2	·836
Belleville ...	·501	10·42	1·228	53·2	·120
Thornycroft ...	·823	10·83	2·180	10·2	1·905
Scotch ...	·870	9·93	1·268	41·2	·266
Herreshoff ...	·930	8·68	2·945	14·8	1·606
Ward (Large) ...	1·122	8·44	3·391	12·3	2·615
Towne ...	1·148	6·77	3·694	21·8	1·317
Scotch ...	1·415	9·06	1·268	41·2	·395
Ward (Launch) ...	1·427	7·01	3·413	13·2	2·586
Locomotive ...	2·220	7·74	1·771	31·3	·978
Locomotive ...	2·728	7·35	1·771	31·3	1·134

TABLE LXXXIX.

MARINE BOILERS.

Ward and Scotch boilers in "Monterey" and navy tugs.

	Weight.	Grate Surface.	Heating Surface.	I.H.P.	Speed of Vessel.
Scotch...	90,040 lbs.	88 sq. ft.	2,840 sq. ft.	373	11·14 knots.
Ward ...	34,720 lbs.	308 sq. ft.	11,880 sq. ft.	524	13·1 knots.

The tests referred to in the next table were carried out by Engineers of the United States Navy, who had the opportunity of testing the two systems of boilers under fairly similar conditions.

Preliminary tests were first made on a boiler which had been in use for several years at the company's works at Elizabethport, New Jersey, with the boiler burning 50lb. of coal per square foot of grate area. This boiler occupied an area on floor of 10½ft. by 8ft., the height being 12ft. 10⅝in., and with heater 15ft. 7in. The total grate area was 38½ square feet, heating surface 1337¼ square feet, excluding 215 square feet in the feed water heater. The weight of the boiler was 39,818lb., and with water it was 49,257lb., equal to 31·7lb. per square foot of heating surface, and 1279·4lb. per square foot of grate area.

The pressure of steam was 171lb., the air pressure in ashpit equal to ·889lb., at the base of smoke pipe ·541lb., and in furnace ·168lb., the draft being forced by a steam jet at the base of the smoke pipe and by a Sturtevant fan. The actual rate of combustion was 44·166lb. of fuel per square foot of grate, but allowing for the dry refuse from the ashpit, 41·077lb. per square foot, the evaporation from and at 212 degrees being 8·472lb. per lb. of actual fuel, or 9·109lb. per lb. of net "combustible." After the test was completed the fires were drawn and the water blown out. Two workmen with two helpers then split both ends of a lower tube, drew it out, put in a new one, expanded it, and replaced the caps ready for water in 22½ minutes. The internal surface was clean, but there was a considerable quantity of soot baked on the outside. There was no cleaning or sweeping during the trial, and after the 24 hours' run 236lb. of soot were removed by a steam jet.

The trials on ship-board are still more significant, since comparison is afforded with Scotch boilers. The American Lake steamers "Zenith City" and the "Victory" are 400ft. long over all, and at 16ft. draught displace 6617·9 tons. They have triple-expansion engines, the "Victory" having cylinders 23in., 38in., and 63in. diameter by 40in. stroke. The high-pressure cylinder of the "Zenith City" is 1in. less, to compensate for higher steam pressure—that is the only difference in machinery. But the "Zenith City" has two Babcock & Wilcox water-tube boilers; the "Victory" two Scotch boilers. The grate surface of the former is 134 square feet, of the latter 144; the heating surface being respectively 6800 and 5715 square feet. Thus the ratio of heating surface to grate area is in the water-tube boilers 50·7 to 1, and in the multitubular boilers 39·6 to 1. The total weight in steaming condition is in the case of the water-tube boiler 173,876lb., in the other 335,787lb.—nearly double—so that the weight per square foot of heating surface is 25·57lb. to 58·7lb. in the old type. Now for results, the water-tube boiler figures being given first in each case. The average horse-power developed on the run, 24 hours in the one case against 9¼ hours in the other, was 1540·19 against 1438·8 I.H.P., which is equal to 11·5 and 9·99 per square foot of grate. The coal burned per square foot of grate area was 25·94lb. against 22·52lb. The economy of consumption was in favour of the multitubular boiler, although the difference is not great, having been 2·256lb.

per I.H.P. per hour against 2·24lb. in the multitubular boiler. In other two trials of shorter duration the water-tube generator only required 2·216 and 2·187lb. per I.H.P. hour and the "Victory" 2·18lb. The water evaporated per lb. of coal was 7lb. in the case of the water-tube boiler, but the water meter got broken in the "Victory." The "Victory" steam pressure was 175lb., and the funnel 50ft. above grate gave a good draught, as high at times as ·4in. The water-tube boilers, it is stated, gave no trouble. There was abundant steam at 200lb. pressure, much steam being wasted through the blow-off valve, owing to irregular firing. As to wetness of steam, that from the water-tube boiler was always drier than that from the multitubular boilers. In the former case the amount of moisture averaged 3-10ths of 1 per cent., against 2¾ per cent. in the case of the Scotch boiler. Finally the weight of the water-tube boilers, including fittings, &c., under steam is 106lb. per I.H.P., less than half that in the case of the multitubular boilers in question.

Table XC.

COMPARISON OF BOILERS IN STEAMERS "ZENITH CITY" AND "VICTORY."

Kind of boilers and number	2 Water-Tube	2 Scotch
Grate surface	134 sq. ft.	144 sq. ft.
Heating surface	6800 sq. ft.	5715 sq. ft.
Ratio of heating surface to grate surface	50·7 to 1	39·6 to 1
Total weight with water	173,876 lbs.	335,787 lbs.
Weight per square foot of heating surface	25·57 lbs.	58·7 lbs.
I.H.P. developed	1540·19	1438·8
I.H.P. per square foot grate surface ...	11·15	9·99
Coal burned per square foot grate surface	25·94 lbs.	22·52 lbs.
Coal burned per I.H.P. per hour ...	2·256	2·24
Duration of run	24 hours	9¼ hours
Steam pressure per square inch ...	200 lbs.	175 lbs.
Moisture in steam	$\frac{3}{10}$ths of 1 %	2¾ %
Weight per I.H.P.	106 lbs.	213 lbs.

Table XCI.

COMPARISON OF WARD AND COWLES BOILERS.

	Ward.	Cowles.
Grate surface ... ... square feet	53	47
Heating surface ... ... square feet	2473·5	2026·75
Ratio of heating surface to grate surface	46·67	43·12
Weight of boiler empty, no smoke pipe ... ... tons	11·84	9·75
Weight of boiler with water ... ... tons	13·85	11·55
Boilers for "Monterey" ... ... number	4	6
Grate surface of each	75	47
Heating surface of each	2,938	1998·5
Weight empty ... ... tons	13·58	9·6
Weight with water ... ... tons	15·86	12·65
Duration of test ... ... hours	24	24·15
Fuel consumed, total ... ... pounds	70,022	45,620
Refuse from fuel ... ... pounds	3,389	6,327
Combustible consumed, total ... ... pounds	66,633	39,293
Total feed water ... ... pounds	461,885	280,822
Temperature of feed ... ... degs.	50·4	58
Steam pressure ... ... pounds	160	160
Air pressure=inches of water	2	2
Coal per hour per square foot of grate surface	55·05	40·19
Combustible per hour per square foot of grate surface ...	52·4	34·62
Apparent evaporation from feed temperature at steam temperature per lb. of coal	6·60	6·16
Same per pound of combustible	6·93	7·15
Actual evaporation per hour for 10 hours' feed at 120°, steam 160 lbs. pressure	19,105	14·192
Actual evaporation per hour per square foot of heating surface	7·724	7·002
H.P. which 1 boiler will furnish from heating surface at 20 lbs. steam per I.H.P. per hour	1139·5	709·6
H.P. from whole number of boilers	4558	4257·6

Table XCII.

COMPARISON OF RESULTS OF TESTS OF THE WARD, THE COWLES, AND THE SCOTCH BOILERS OF THE "SWATARA," EACH MADE WITH AN AIR PRESSURE = 2 INCHES WATER.

	Ward.	Cowles.	Scotch.
	lbs.	lbs.	lbs.
1. Coal per square foot heating surface, per hour	1·1795	·93204	1·0658
2. Combustible, ... „	1·1224	·80278	·8717
3. Water evaporated, ... „	6·8093	5·7376	6·9710
4. Equivalent evaporation from and at 212° and atmospheric pressure ...	8·2941	7·3287	8·7678
5. Evaporation per hour per cubic foot space occupied, and as above ...	18·6075	14·0188	8·396
6. Evaporation per hour per ton of steaming weight, and as above	1485·4	1209·8	455·762

TABLE XCIII.—TRIALS OF VARIOUS MARINE BOILERS.

Kind of boiler and maker ... / Where used ...	Tubulous, Thornycroft, U.S.S. "Cushing."				Tubulous Towne On shore.		Tubulous Cowles On shore.	Tubulous Ward On shore.	Shell cylindrical single-ended s.s. "Iona."	Shell locomotive Italian tor. cr. "Tripoli" and "Folgore."	
Outside dimensions ...	10′ × 7′ × 8′				6′9½″ × 5′4″ × 8′		11′5″ × 7′9″ × 12′2″	10′3 diam. 11′8″ high	13′3″ diam. 10′ long	16′8 × 6′4″ × 7′6″	
Grate surface, ... square feet	38				1·56		47	53	21	28	
Heating surface, ... square feet	2451				577·0		2026·75	2473·5	1580	1116	
Ratio heating surface div. by grate surface ...	64·5				37·0		43·12	46·67	75·2	39·8	
Weight of boiler, empty, ... tons	9·00				3·57		9·75	11·84	29·30	—	
" " and water ... tons	11·00				4·52		11·55	13·85	47·17	15·60	
Duration of trial ... hours	2·5	11·5	11·5	1·0	6·25	6·5	12	12	16	—	—
Air pressure in inches of water ...	*0·0	0·35	3·0	4·0	†0·0	2·0	2·0	2·0	‡0·2	3·13	4·95
Feed temperature ... degrees Fah.	52	58·5	58	52	45·3	39	58	50·4	106	—	—
Steam pressure above atmosphere— ... lbs.	250	250	250	250	160	160	160	160	165.	125	123
Coal per hour per sq. foot grate surface— ... lbs.	7·58	24·12	40·23	66·32	14·35	33·78	40·19	55·05	22·4	98·6	120·8
Refuse— ... per cent.	6·11	8·04	7·53	6·27	10·65	8·82	13·87	4·84	2·9	—	—
Moisture ... "	8·09	2·11	3·89	6·68	8·66	10·62	—	12·48	2·87	—	—
Superheating ... "	—	—	—	—	—	—	5·7	—	—	—	—
(a) Apparent evaporation from temperature feed at temperature steam per lb. coal ...	10·55	8·13	7·53	5·69	6.36	5·30	6·16	6·60	9·15	—	—
(b) Same from and at 212° Fah. ...	12·95	9·93	9·19	6·98	7·78	6·51	7·45	8·04	10·63	6·97	6·62
Actual evaporation as in (a) ...	9·69	7·96	7·23	5·30	5·82	4·74	6·16	6·00	8·90	—	—
Same as in (b) ...	11·90	9·72	8·84	6·51	7·12	5·82	7·45	7·31	10·20	6·97	6·62
Actual evaporation from and at 212° Fah. per square foot of heating surface ...	1·40	3·63	5·51	6·70	2·76	5·32	6·96	8·62	3·08	17·20 ‖	20·09 ‖
Horse power per 100 square feet of heating surface on basis of 20 lbs. steam per hour from and at 212° Fah. ...	7·00	18·15	27·55	33·50	13·80	26·60	34·80	43·10	15·40	86·00 ‖	100·45 ‖
Horse power per ton of boiler and water on same basis ...	15·6	40·44	61·38	74·65	17·60	33·90	61·07	76·98	5·16	61·52 ‖	71·85 ‖

* Blowers discharging into open fire room. † Smoke pipe 21 ft. 6 ins. above grate. ‡ Smoke pipe 52 ft. above grate.

‖ These figures appear to be erroneous—see Trans. I.N.A., Vol. 29, pp. 30 and 36.

TABLE XCIII. *continued.*—TRIALS OF VARIOUS MARINE BOILERS.

Kind of boiler and maker / Where used	Tubulous Belleville On Shore.		Tubulous B. & W. "Zenith City."	Tubulous B. & W. On Shore.	Cylin. Sing. End "Wheeling."	Tubulous B. & W. "Marietta."	Cylin. Gunboat "Concord."	Tubulous Normand proposed.
Outside dimensions	11′ 6″ × 8′ 9″ × 17		14′ 8″ × 12′ 2″ × 8′ 8″	15′ 7″ × 10′ 6″ × 8′	10′ 6″ dia. 10′ 6″ long.	11′ 7″ × 11′ 7″ × 11′ 5½″	9′ 9″ dia. 17′ 9″ long.	10′ × 12′ 4″ × 18′ 7″
Grate surface, ... square feet	91·4		67	38·5	30	47	55	95
Heating surface, ... square feet	2900		3400	1552	1254	1832	2052	4650
Ratio heating surface div. by grate surface	31·73		50·7	40·31	41·81	38·98	37·31	48·95
Weight of boiler, empty, ... tons	36·0		31·85	17·78	25·91	23·24	30·19	36·87
" " and water, ... tons	38·0		39·26	21·99	36·85	27·26	45·18	46·00
Duration of trial— ... hours	—	—	10	24	4	4	4	24
Air pressure in inches of water	*a* 6·3	*a* 8·0	Nat. draught	0·9	0·78	0·36	2·3	—
Feed temperature— ... degrees Fah.	42	42	118	58·5	104	121	140	—
Steam pressure above atmosphere— ... lbs.	260	260	195	156·3	182	174	164·3	220
Coal per hour per sq. foot grate surface— ... lbs.	18	24	26·6	44·2	30·92	24·47	42·74	27·2
Refuse— ... per cent.	11·5	5·4	8·8	7·0	4·0	4·0	3·7	—
Moisture ... "	—	—	0·3	2·0	—	—	—	—
Superheating ... "	—	—	—	—	—	—	—	—
(*a*) Apparent evaporation from temperature feed at temperature steam per lb. coal	8·78	8·47	7·01	7·01	*c* 8·62	*c* 7·25	*c* 5·80	—
(*b*) Same from and at 212° Fah.	10·81	10·42	8·06	8·47	*c* 10·0	*c* 8·26	*c* 6·51	—
Actual evaporation as in (*a*)	—	—	—	—	—	—	—	—
Same as in (*b*)	10·81	10·42	8·04	8·31	*c* 10·0	*c* 8·26	*c* 6·51	10·0
Actual evaporation from and at 212° Fah. per square foot of heating surface	4·99	6·41	4·21	9·11	*c* 7·40	*c* 5·19	*c* 7·46	5·56
Horse power per 100 square feet of heating surface on basis of 18 lbs. steam per hour from and at 212° Fah.	27·72	35.61	23·39	50·62	*b* 43·05	*b* 28·76	*b* 41·47	30·91
Horse power per ton of boiler and water on same basis	21·15	27·18	20·26	35·73	*b* 14·65	*b* 19·33	*b* 18·84	31·25

a Nat. draught air mixer. *b* Actual trial trip. *c* Estimate from coal=18lbs. steam per I.H.P

TABLE XCIV.—TABULATED RESULTS OF TESTS OF ELEPHANT AND WATER-TUBE BOILERS MADE AT SAN FRANCISCO, ACCORDING TO FORMS Nos. 80-4 AND 80-5 OF THE U.S. NAVY DEPARTMENT.

	Babcock and Wilcox.	Heine.	Elephant.
Average steam pressure, absolute, p ...	119·76	117·67	116·785
Average temperature of feed water, t ...	150·1	130·73	135·69
(a) No. of lbs. of water evaporated, $W_1 \times Q$ ...	135,832·35	95,446·14	168,441·57
(b) No. of lbs. of water carried over with steam, $W_1 (1-Q)$ ...	1818·50	674·02	1191·33
Total heat of steam at pressure p ...	1185·98	1185·576	1185·41
Total heat of water at temperature t_1 ...	118·32	98·845	103·91
(c) Units of heat to vaporise 1lb. water from t at p ...	1067·66	1086·73	1081·50
(c_1) Units of heat to raise 1lb. water from t_1 to temperature of p ...	194·59	212·70	207·0
(d) Units of heat to vaporise 1lb. water from and at 212° F. and atmospheric pressure ...	965·7	965·7	965·7
Total heat required to vaporise the water $a \times c$ ...	145,022,766·8	103,724,183·7	182,169,557·9
Total heat required to raise the temperature of the water $b \times c_1$ ...	353,861·9	143,364·0	246,605·3
(e) Total heat obtained from fuel measured by steam discharged ...	145,376,628·7	103,867,547·8	182,416,163·3
(f) Units of heat obtained per pound of dry fuel ...	6254·9	7341·82	7355·63
(g) Units of heat obtained per lb. of dry combustible ...	7606·75	8753·83	9036·1
$\left(\frac{f}{c}\right)$ Potential evaporation per lb. fuel from t_1 at p ...	5·8585	6·7558	6·8013
$\left(\frac{g}{c}\right)$ Potential evaporation per lb. combustible from t_1 at p ...	7·1246	8·0550	8·3551
$\left(\frac{f}{d}\right)$ Equivalent evaporation per lb. fuel from 212° at atmospheric pressure ...	6·4770	7·6025	7·6168
$\left(\frac{g}{d}\right)$ Equivalent evaporation per lb. combustible from 212° at atmospheric pressure ...	7·8769	9·0647	9·357
Total quantities. Duration of test in hours ...	19·8833	19·9033	20·1
Total quantities. Wet fuel consumed ...	23,760·85	14,577·8	25,761·13
Total quantities. Moisture in fuel ...	518·83	430·42	961·62
Total quantities. Refuse from fuel (dry ashes, dust and clinkers) ...	4130·5	2282·	4612·
Total quantities. Combustible consumed ...	19,111·52	11,865·38	20,187·51
Total quantities. Water fed to boilers by tank measurement W_1 ...	137,650·85	96,120·16	169,632·9
Total quantities. Per cent. of fuel in dry refuse, etc. ...	17·43	15·72	17·98

TABLE XCIV. *continued.*—TABULATED RESULTS OF TESTS OF ELEPHANT AND WATER-TUBE BOILERS MADE AT SAN FRANCISCO ACCORDING TO FORMS Nos. 80-4 AND 80-5 OF THE U.S. NAVY DEPARTMENT.

		Babcock and Wilcox.		Heine.		Elephant.	
Average quantities.	Temperature of feed water t_1	150·129°		130·728°		135·69°	
	Temperature of steam by thermometer	340·39° 331·29°		343·43° 339·65°		339·89° 331·96°	
	Temperature of uptake	510·70°		569·42°		458·89°	
	Temperature of atmosphere	64°		62°		53°	
	Temperature of fire-room	82°		71·22°		69·1	
	Barometer in inches of mercury	29·78		29·968		30·061	
	Pressure of steam at boiler in lbs. per sq. in. above perfect vacuum						
	14·62 14·76 14·71 } +pressure by gauge in lbs. p	119·76		117·673		116·785	
Rates of Combustion.		Dry Fuel.	Combustible.	Dry Fuel.	Combustible.	Dry Fuel.	Combustible.
Amount consumed per hour, dry		1168·92	961·184	710·8	596·15	1233·8	1004·35
Amount consumed per square foot of grate surface		31·18	25·64	34·3	28·77	20·57	16·74
Vaporisation in Pounds of Water.		Per lb. of Fuel.	Per lb. of Comb.	Per lb. of Fuel.	Per lb. of Comb.	Per lb. of Fuel.	Per lb. of Comb.
Apparent evaporation by tank measurement from temperature t and under pressure p ...		5·922	7·2025	6·794	8·1008	6·840	8·403
Equivalent apparent evaporation from and at 212° and under atmospheric pressure ...		6·5477	7·963	7·645	9·116	8·201	10·075
Actual evaporation into steam of quality Q, from temperature t_1 and under pressure p ...		5·848	7·1073	6·746	8·044	6·792	8·3438
Equivalent actual evaporation from and at 212° and under atmospheric pressure		6·4613	7·8577	7·592	9·0522	7·6065	9·3443
Potential evaporation, or evaporation if all the heat obtained from fuel had been used in converting the water into dry saturated steam from temperature t_1 and under pressure p ...		5·8585	7·1246	6·7558	8·0550	6·8013	8·3551
Equivalent potential evaporation from and at 212° and under atmospheric pressure ...		6·477	7·8769	7·6025	9·0647	7·6163	9·3570

Thornycroft Boiler. — Careful experiments conducted by Professor A. B. W. Kennedy with the Thornycroft Water-tube Boiler gave the following results :—

TABLE XCV.

TRIALS OF THORNYCROFT MARINE BOILERS.

	A	D	C	B	E
Date	Nov. 21, 1888	Nov. 26, 1888	Nov. 24, 1888	Nov. 22, 1888	Nov. 29, 1888
Duration	5 hrs. 2 min.	4 hrs. 57 min.	5 hrs. 9 min.	4 hours.	2 hours.
Atmospheric pressure	14·80 lbs. per sq. in.	14·55 lbs. per sq. in.	14·80 lbs. per sq. in.	14·84 lbs. per sq. in.	14·45 lbs. per sq. in.
Boiler pressure	186·00lbs. per sq. in.	181·80 lbs. per sq. in.	171·20 lbs. per sq. in.	149·40 lbs. per sq. in.	180·50 lbs. per sq. in.
Boiler pressure, absolute ...	200·80 lbs. per sq. in.	196.35 lbs. per sq. in	186·00 lbs. per sq. in.	164·24 per sq. in.	194·95 per sq. in.
Air pressure in stokehold ...	0·00	0·00	0·27	0·49 in.	2·00 in.
Air temperature in stokehold ...	—	69·3° Fah.	71·4° Fah.	60·3° Fah.	62·1 Fah.
Total weight of coal used ...	1680·0 lbs.	1006·5 lbs.	2877·0 lbs.	3575·0 lbs.	3503·0 lbs.
Total weight of ashes	270·0 lbs.	233·5 lbs.	197·0 lbs.	—	192·0 lbs.
Weight of ashes re-used ...	None.	233·5 lbs.	170·0 lbs.	None.	192·0 lbs.
Coal burnt per hour	334·0 lbs.	203·3 lbs.	559·0 lbs.	894·0 lbs.	1751·0 lbs.
Area of fire grate	30 sq. ft.	26·2 sq. ft.	30 sq. ft.	30 sq. ft.	26·2 sq. ft.
Coal burnt per ft. grate per hr.	11·10 lbs.	7·74 lbs.	18·60 lbs.	29·80 lbs.	66·80 lbs.
Total feed water used	—	11291·7 lbs.	30141·0 lbs.	34332·0 lbs.	31109·0 lbs.
Feed used per hour	—	2281 lbs.	5852 lbs.	8583 lbs.	15554 lbs.
Feed temperature	78·4° Fah.	76·3 Fah.	78·0 Fah.	83·8° Fah.	111·2° Fah.
Steam temperature	382° Fah.	380·2° Fah.	375·5° Fah.	365·5° Fah.	379·6° Fah.
Factor of evaporation	1·192	1·194	1·191	1·182	1·158
Water evap. per lb. fuel (*a*) Ash not re-used ...	—	—	—	9·60 lbs.	—
Water evap. per lb. fuel (*b*) With ash utilised ...	—	11·22 lbs.	10·48 lbs.	[10·20 lbs.]	8·89 lbs.
Equivalent evaporation from and at 212° F. (*a*)	—	—	—	11·35 lbs.	—
Equivalent evaporation from and at 212° F. (*b*)	—	13·40 lbs.	12·48 lbs.	[12·00 lbs.]	10·29 lbs.
Equivalent evaporation from and at 212° F. per lb. carbon value in fuel	—	13·08 lbs.	12·18 lbs.	[11·70 lbs.]	10·04 lbs.
Temperature of gases in chimney	474° Fah.	421° Fah.	540° Fah.	610° Fah.	777° Fah.
Air pressure in chimney ...	0·00 in.	0·00 in.	+ 0·03 in.	+ 0·12 in.	+ 0·40 in.
Total heating surface	1837 sq. ft.	1837 sq. ft.	1837 sq. ft.	1837 sq. ft.	1837 sq. ft.
Ratio of heating surface to grate area...	61·2	70·1	61·2	61·2	70·1
Water evaporated per sq. ft. of heating surface per hr.	—	1·24 lb.	3·20 lbs.	4·70 lbs.	8·50 lbs.
Mean rate of transmission of heat per sq. ft. H.S. per min.	—	23·8 heat units.	61·0 heat units.	89 heat units.	158 heat units.
Lbs. coal per I.H.P. per hour ...	2·220	2·280	1·981	1·990	2·260
Efficiency of boiler	—	86·8 per cent.	81·4 per cent.	78·2 per cent.	66·6 per cent.

Descriptive details of these trials, with analyses of the fuel and gases, and statements of the heat balances, will be found in Professor Kennedy's Report, which is attached to Mr. Thornycroft's paper in Min. Proc. Inst. C. E., Vol. xcix., pp. 41–147.

Belleville Boiler.—The following results afford a contrast in some points between the ordinary cylindrical or "Scotch" boiler and water-tube boilers of the Belleville design. The experiments were published under the authority of Mr. Samson, of Messrs. Maudslays, the British makers of the Belleville boiler:—

In order to ascertain the comparative evaporative efficiency between the ordinary cylindrical single-ended boiler and boilers of the Belleville type, the following trials were made:

A vessel with cylindrical single-ended, three-furnace boilers was selected. Two of these boilers worked in battery were used, the total grate surface being 138 square feet, and the total heating surface 3,880 square feet. A group of four Belleville boilers, having a total grate surface of 135 square feet, and heating surface 3,842 square feet, was then selected for experiment. It will be observed that as regards grate and heating surface, the boilers above mentioned are practically identical, the cylindrical with the water-tube. Trials were made in order to ascertain how many pounds of water could be converted into dry steam per pound of coal, burning the same with natural draught and at approximately equal rates of combustion. The vessels were moored alongside the quay, and the water was taken from the town main and measured carefully into tanks before being pumped into the boilers. The trials were made at the same place, by the same staff, with the same quality coal, and under as nearly as possible the same conditions, in order to render the comparative trials perfectly fair. The results were as under:

Table XCVI.

BELLEVILLE BOILERS—EVAPORATIVE TRIALS.

Four Boilers—

Total heating surface ... ... 3842 sq. ft.
" grate " ... ... 135 "

Duration of Trial.	Coal Consumed in Pounds per Square Foot of Grate.	Water Evaporated per Pound of Coal from Temperature of Feed.	Equivalent Evaporation from and at 212°.	Steam Pressure in Boilers.	Temperature of Feed Water.	Quality of Coal.
hours		lb.		lb.	deg. Fahr.	
8	18·8	8·3	10·24	200	40	Best
8	19·43	9·1	11·22	200	40	Welsh
8	19·4	9·0	11·09	200	40	"
8	24·5	7·83	9·58	200	50	"
8	12·0	8·5	10·38	200	50	"
8	12·0	9·16	11·30	200	50	"
8	9·2	8·64	10·57	200	50	"

TABLE XCVI. *continued.*

SINGLE-ENDED CYLINDRICAL BOILERS.

Grate surface ... ... 138 sq. ft.
Heating „ ... ... 3880 „

Duration of Trial.	Coal Consumed in Pounds per Square Foot of Grate.	Water Evaporated per Pound of Coal from Temperature of Feed.	Equivalent Evaporation from and at 212.°	Steam Pressure in Boilers.	Temperature of Feed Water.	Quality of Coal.
hours		lb.		lb.	deg. Fahr.	
8	12	7·59		124	50	Best
8	20	8·02		124	50	Welsh.
8	28	7·85		138	50	„
8	12	8·44		110	50	„
8	20	8·09		110	50	„
8	28	7·86		132	50	„

It should be noted that the above results were obtained from cold feed water, and that the water-tube boiler raised steam to 200 lb pressure against the cylindrical boiler at from 110 lb. to 138 lb.

This was necessary in order to make the comparative trials perfectly fair, because although in the Belleville boiler steam was raised to 200 lb. per square inch, it was reduced to 135 lb. per square inch at the engines, whereas in the cylindrical single-ended boilers the engines were supplied direct from the boiler at the working pressure.

The cylindrical boilers were to Admiralty scantlings, and weighed, together with water, lagging, fittings, and uptakes complete, about 100 tons. The Belleville boilers weighed with castings, brickwork, fittings, water, and all appurtenances peculiar to the system, about 50 tons, showing a saving of, say, 50 tons in favour of the water-tube boiler.

Some interesting results obtained from trials with Lagrafel-D'Allest, Niclausse and other boilers, and arranged for comparison with some cylindrical boiler tests, were given by Mr. J. T. Milton, Chief Engineer-Surveyor of Lloyds Register, in a lecture on water-tube boilers at the Royal United Service Institution (June 26th, 1895). They were as follows :—

TABLE XCVII.—RESULTS OF TRIALS MADE WITH LAGRAFEL-D'ALLEST BOILERS.

Description of boiler.	Duration of trial.	Grate surface.	Heating surface.	Consumption of Cardiff coal per square foot of grate per hour.	Actual evaporation of water per hour from feed temperature per lb. of coal.	Equivalent evaporation from and at 212°.	Remarks.
	hours.	square feet.	square feet.	lbs.	lbs.	lbs.	
Part of installation of vessel of 2,000 I.H.P.	3	Total in vessel. 100·75	Total in vessel. 4,090	45·75	8·24	9·39	
	3			35·84	9·07	10·34	
	3			15·36	9·43	10·75	
Part of installation of vessel of 9,000 I.H.P.	6	Total in vessel. 645	Total in vessel. 21,528	20·48	9·80	11·26	These trials were conducted by French Naval Officers.
	12			12·30	10·07	11·53	
	3			24·60	9·50	10·86	
	3			30·72	9·23	10·58	
Experimental boiler ...	6	35·9	1,076	10·29	10·67	12·44	
Do.	$6\frac{3}{4}$	30·8	1,076	15·15	9·58	11·15	
Do.	6	35·9	1,076	15·50	9·23	10·83	
Do.	6	43·0	1,076	15·36	8·97	10·43	
Do.	3	35·9	1,076	25·09	8·02	9·42	
Do.	3	35·9	1,076	31·00	8·75	10·28	
RESULTS OF TRIALS OF OLDER FORM OF LAGRAFEL BOILER.							
Lagrafel	6	35·9	1,076	15·14	6·72	7·78	Do.
Do.	3	35·9	1,076	15·14	5·43	6·34	
Do.	3	35·9	1,076	20·22	6·53	7·62	
RESULT OF TRIAL WITH ANDERSON AND LYALL'S BOILER.							
	5	8·8	475	18·29	10·0	12·05	This trial was conducted by Mr. Stromeyer, of Lloyd's Register.
MEAN RESULTS OF TWO SERIES OF TRIALS ON DIFFERENT VESSELS FITTED WITH BELLEVILLE BOILERS *under Sea-going Conditions.*							
		135	3,842	12		10·73	These results have been communicated by Messrs. Maudslay and Co.
		135	3,842	20		10·94	
		135	3,842	25		10·33	
		135	3,842	30		9·5	

TABLE XCVII. *continued.*—RESULTS OF TRIALS OF CYLINDRICAL BOILERS FITTED WITH SERVE TUBES, RETARDERS, AND INDUCED HOT-AIR FEED, USING NIXON'S NAVIGATION COAL.

Description of boiler.	Duration of trial.	Grate surface.	Heating surface.	Consumption of Cardiff coal per square foot of grate per hour.	Actual evaporation of water per hour from feed temperature per lb. of coal.	Equivalent evaporation from and at 212°.	Remarks.
Cylindrical Marine type	7	32	Heat absorbing surface of tubes 1,306 sq. feet.	33·22	9·25	10·83	These trials were made at Sir J. Brown and Co.'s Works, Sheffield, and the results taken from Trans. Nav. Arch., 1894.
	48		Heating surface of furnaces and chamber, 170 sq. feet.	43·79	8·91	10·5	
	7		Total, 1,476 sq. feet.	45·5	9·74	11·44	
		Ratio 1 to 46.					

RESULTS OF TRIALS OF CYLINDRICAL BOILERS ON BOARD SHIP.

Under Sea-going Conditions, as recorded in the Reports of the Research Committee of the Institution of Mechanical Engineers.

Description of boiler.	Duration of trial.	Grate surface.	Heating surface.	Consumption of Cardiff coal per square foot of grate per hour.	Actual evaporation of water per hour from feed temperature per lb. of coal.	Equivalent evaporation from and at 212°.	Remarks.
s.s. "Meteor"	17	208	5,760	19·25	7·46	8·21	Scotch Coal of 12,790 T.U. Calorific value.
s.s. "Fusi Yama"	14	52	2,257	18·98	7·96	8·87	West Hartley Coal, 12,760 T.U. Calorific value.
Twin s.s. "Colchester" ...	11	220	5,820	26·1	7·49	8·53	Yorkshire and Nottinghamshire 13,280 T.U. Calorific value.
s.s. "Iona"	16	42	3,160	22·4	9·15	10·63	Northumberland Coal, 14,830 T.U. Calorific value.
p.s. "Ville de Douvres" ...		236	7,340	31·3	8·97	9·84	Patent Fuel, 14,390 T.U. Calorific value.

The following results were published by Sir John Durston[1]:—

TABLE XCVIII.

Name of Ship and Type of Boiler.	Duration of Trials. Hours.	Coal burnt per sq. ft. of grate. lbs. per hour.	Equivalent evaporation from and at 212 deg. F. Per sq. ft. heating surface p. hour.	Equivalent evaporation from and at 212 deg. F. Per lb. of coal.	Ratio of heating surface to grate.	Remarks.
"Seagull," fitted with Niclausse boilers	8	14·60	4·91	10·77	31·9	Trials on board.
	8	24·20	7·31	9·61	31·9	Trials on board.
"Sheldrake," fitted with Babcock and Wilcox boilers ...	5	22·50	5·95	12·10	45·7	Trials on shore.
	8	15·00	5·29	12·70	36·1	Trials on board.
	8	25·00	7·68	11·10	36·1	Trials on board.
"Sharpshooter," fitted with Belleville boilers without economisers	8	21·00	7·85	11·05	29·6	Trials on board.
	8	13·10	4·70	10·65	29·6	Trials on board.
	8	9·90	3·53	10·55	29·6	Trials on board.
Belleville boiler with economisers. Average of several trials	4	30·13	11·79	11·67	31·3	Trials on shore.

Particulars of extended trials of some of these boilers are given in the following Table, which was first published in the *Naval and Military Record* of November 23rd, 1899. That paper remarked that :—

At present the gunboat *Seagull* which has been fitted with the Niclausse type of water-tube boiler, is being subjected to exactly similar experimental tests as the *Sheldrake* and *Sharpshooter* have undergone, the former recently with the Babcock and Wilcox type of water-tube boiler, and the *Sharpshooter* a few years since with the Belleville class. When the *Seagull* has completed her programme, the results of the working of the three types of boilers will be collated for purposes of comparison as to their respective merits. As this comparison is likely to be made early in the ensuing year, it may be interesting to give the hitherto unpublished return relating to the trials of the *Sharpshooter* and *Sheldrake*.

[1] See Min. Proc. Inst. C.E., Vol. cxxxvii., p. 213.

TABLE XCIX.

H.M.S. SHELDRAKE.

BABCOCK AND WILCOX BOILER. 4 IN No.

Nature of Trial.	Duration in hours.	Steam Pressure.	I.H.P.	Air Pressure.	Coal per I.H.P. All purposes.	Coal per square foot grate.	Water per lb. coal.	Grate surface.
1898-9.								
Evaporative	8	168	1116	0	1·69	15	10·5	126
"	8	179	1292	0	1·46	15	10·5	126
"	8	159	1761	...	1·78	25	9·05	126
"	8	165	1873	...	1·67	25	9·34	126
8 hours at 2,500 indicated horse-power	8	152	2651	0	1·42	15	...	252
3 hours at 3,000 indicated horse-power	3	152	4092	·43	1·58	25·6	...	252
3 hours commissioning	3	119	2735	·14	1·64	27·8	...	252
1,000 miles at 1,500 indicated horse-power	69	120	1303	0	1·61	12·3	...	189
" " "	68	120	1506	0	1·6	12·67	...	189
" " "	70	135	1534	0	1·75	14·2	...	189
" " "	68½	130	1539	0	1·59	15·1	...	189
1,000 miles at 1,300 indicated horse-power	67	135	1839	0	1·6	15·4	...	189
" " "	66½	140	1838	0	1·68	16·4	...	189
1,000 miles at 2,000 indicated horse-power	59	145	2033	0	1·57	17·0	...	189
" " "	61½	140	2042	0	1·56	16·8	...	189
1,000 miles at 2,150 indicated horse-power	56¾	150	2245	0	1·63	19·4	...	189
Total	632¼							
Mean		146	1974		1·63	9·85		

TABLE C.

H.M.S. SHARPSHOOTER.

BELLEVILLE BOILER. 8 IN No.

Nature of Trial.	Duration in hours.	Steam Pressure.		I.H.P.	Air Pressure.	Coal per I.H.P. All purposes.	Coal per square foot grate.	Water per lb. coal.	Grate surface.
		Engines.	Boilers.						
1894-5.									
Evaporative	8	112	209	974	0	2·6	18·8	8·27	135
"	8	125	194	1133	0	3·3	19·43	9·07	135
"	7	124	196	1087	0	2·4	19·4	9·0	135
8 hours to obtain 2,500 I.H.P.	8	149	216	2612	...	1·98	19·4	...	270
Maximum power	8	143	183	3220	·13	2·05	24·5	...	270
3 hours commissioning	3	144	204	2523	0	...	...	...	270
1,000 miles at 1,500 I.H.P.	48½	120	210	1553	0	1·67	14·4	...	202
" " " " "	69	120	210	1549	0	1·91	14·6	...	202
" " " " "	66½	135	210	1569	0	2·07	16·0	...	202
" " " " "	68	130	225	1554	0	1·94	14·9	...	202
" " " 1,800 I.H.P.	66¾	135	210	1804	0	1·92	17·2	...	202
1,000 miles at 1,800 I.H.P.	69½	140	220	1830	0	1·84	16·6	...	202
" " " 2,000 "	65	145	220	2016	0	1·8	17·9	...	202
1,000 miles at 2,000 I.H.P.	63½	140	220	2037	0	1·79	18·0	...	202
" " " 2,150 "	62	150	225	2194	0	1·73	18·8	...	202
Totals	620¾								
Mean				1843		2·00	16·66	8·78	

TABLE CI.—PARTICULARS OF BOILERS IN RECENT CRUISERS.

Name of Ship	Andromeda.	Hermes.	Don Carlos I.	Hai Chi.	Æolus.	Pallas.
Number and type of boiler fitted	30 Belleville.	18 Belleville.	12 Yarrow.	8 cylindrical, 4 D.E. 4 S.E.	5 cylindrical. 3 D.E. 2 S.E.	4 cylindrical. D.E.
Steam pressure in lbs. per square inch	300	300	300	155	155	155
I.H.P. with natural draught	16500	10000	8000	12000	7000	5000
I.H.P. with forced draught	—	—	12500	17000	9000	7500
Total heating surface in square feet	40140	24050	32004	27558	15947	11040
Heating surface per I.H.P., natural draught	2·44	2·405	4·0	2·3	2·28	2·2
Heating surface per I.H.P., forced draught	—	—	2·56	1·62	1·77	1·475
Total grate area in square feet	1439	750	587	940	560	406
Length of fire bars	6 ft. 3 in.	6 ft. 3 in.	7 ft. 3 in.	7 ft. 1½ in.	7 ft.	7 ft. 3 in.
I.H.P. per square foot of grate, natural draught	11·47	13·33	13·6	12·78	12·5	12·3
I.H.P. per square foot of grate, forced draught	—	—	21·3	18·1	16·05	18·4
Total boiler room area in square feet	4925	3100	2440	3470	2230	1900
I.H.P. per sq. ft. boiler room area, natural draught	3·35	3·22	3·28	3·46	3·14	2·63
I.H.P. per sq. ft. boiler room area, forced draught	—	—	5·12	4·9	4·03	3·94
Heating surface per sq. ft. boiler room area	8·15	7·77	13·1	7·94	7·16	5·82
Grate area per sq. ft. boiler room area	·292	·242	·24	·276	·251	·214
Grate area per sq. ft. on basis of 6ft. 3in. bars	·292	·242	·207	·242	·22	·185
Total weight of boilers, up-takes and funnels, in tons	559	342	217	447	270	174
Total weight of water in boilers in tons	43	30	30	197	103	82
Total weight of pumps, pipes, connections, water in feed tanks, &c., in tons	168	100	82	97	55	41
Total weight in boiler room, in tons	770	472	329	741	428	297
Weight in boiler rooms in lbs., per I.H.P., natural draught	104	105·5	92·2	138	137	133
Weight in boiler rooms in lbs., per I.H.P., forced draught	—	—	59	97·4	106·3	89
I.H.P. per ton boiler room weight, natural draught	21·4	21·19	24·3	16·2	16·4	16·8
I.H.P. per ton boiler room weight, forced draught	—	—	38·0	22·9	21·1	25·2

The preceding Table is from a paper "On the Boiler arrangements of certain recent cruisers" by Mr. F. T. Marshall, M.I.N.A. The vessels referred to are H.M.S. "Andromeda," built at H.M. Dockyard at Pembroke ; H.R. Portuguese M.S. "Don Carlos I.", built at Elswick ; H.I. Chinese M.S. "Hai Tien" and "Hai Chi," sister vessels, also built at Elswick ; and H.M.S. "Hermes," "Œolus," and "Pallas," the two latter being included as being typical second and third class cruisers with cylindrical boilers.

Boilers in the British Navy.—A comprehensive view of the position as regards boilers in the vessels of the British Navy is afforded by the Tables given in Sir John Durston's two papers on "The Machinery of Warships."

The following Table is taken from the latter paper on account of the details of dimensions which it gives.

TABLE CII.

—	Steam-Pressure. Boilers. Engines.	I.H.P. (a) Full Power, F. D. (b) Full Power N D. (c) Continuous.	Floor Space. Engine Room. Length × Mean Width.	Floor Space. Engine Room. Square Feet per I.H.P.	Floor Space. Boiler Rooms. Length × Mean Width.	Floor Space. Boiler Rooms. Square Feet per I.H.P.	Floor Space. Total Square Feet per I.H.P.	Weight of Machinery (Main) excluding Auxiliaries and Propellers, &c. Engine Room.	Weight … Boiler Rooms.	Weight … Per I.H.P. Engine Room.	Weight … Per I.H.P. Boiler Rooms.	Weight … Total per I.H.P.	Piston Speed.	Stroke.	Revolutions.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
			Feet. Feet.		Feet. Feet.			Tons.	Tons.	Lbs.	Lbs.	Lbs.	Feet per Minute.	Inches.	Per Minute
A Majestic[1]	155 / 150	(a) 12,000 (b) 10,000 (c) 8,000	43·5 × 40·0	(b) 0·200	79·5 × 45·5	(b) 0·362	(b) 0·562	443	721	98	161	(b) 259	850	51	100
A Venus	155 / 150	(a) 9,600 (b) 8,000 (c) 4,800	46·0 × 33·5	(b) 0·200	81·0 × 38·2	(b) 0·385	(b) 0·585	278	547	76	153	(b) 231	910	39	140
A Royal Sovereign[1]	155 / 150	(a) 13,000 and 11,000 (b) 9,000 (c) 3,400	44·0 × 40·0	(b) 0·196	76·0 × 40·0	(b) 0·340	(b) 0·536	397	393	99	148	(b) 247	918	51	108
A Crescent	155 / 150	(a) 12,000 (b) 10,000 (c) 6,000	40·0 × 46·0	(b) 0·184	93·5 × 37·0	(b) 0·345	(b) 0·530	365	644	82	144	(b) 226	850	51	100
B Powerful[1]	260 / 210	(a) .. (b) 25,000 (c) 18,000	60·0 × 42·0; 18·0 × 28·0 for auxiliary machinery.	(b) 0·103; 0·02[2]; 0·123	112·0 × 42·0; 74·0 × 34·0	(b) 0·290	(b) 0·413	799	1156	73	104	(b) 178	880	48	110
B Arrogant	300 / 250	(a) .. (b) 10,000 (c) 7,000	48·0 × 35·5	(b) 0·171	101·0 × 31·0	(b) 0·313	(b) 0·484	288	462	65	103	(b) 168	910	39	140
C Pelorus	300 / 250	(a) 7,000 (b) 5,000 (c) 3,500	37·6 × 34·0	(b) 0·257	80·0 × 24·0	(b) 0·384	(b) 0·640	164	173	74	79	158	900	27	230
D Diadem	300 / 250	(a) .. (b) 16,500 (c) 12,500	55·3 × 43·5	(b) 0·147	66·0 × 36·0; 66·0 × 40·0	(b) 0·305	(b) 0·452	580	766	79	104	(b) 183	880	48	110
D Argonaut	300 / 250	(a) (b) 18,000 (c) 13,500	55·0 × 43·0	(b) 0·132	66·0 × 39·0; 65·0 × 34·3	(b) 0·267	(b) 0·400	593	794	74	80	(b) 178	960	48	120
D Canopus[1]	300 / 250	(a) (b) 13,500 (c) 10,250	44·0 × 46·0	(b) 0·150	84·0 × 43·25	(b) 0·270	(b) 0·420	440[4]	626[4]	73[4]	104[4]	177[4]	918[4]	51	108

[1] Separate auxiliary machinery room. [2] Evaporator and dynamos stowed in engine-room. [3] Auxiliary. [4] Estimated.

In his paper on "The Machinery of Warships," in 1894,[1] Mr. Durston gave details of the machinery fitted in the 70 vessels built under the Naval Defence Act of 1889. In "Recent Trials of the Machinery of Warships," published in 1899,[2] Sir A. J. Durston and Mr. H. J. Oram give similar details of the vessels added to the Royal Navy since the former date.

It appears that ten Battleships with water tank boilers, which are among the recent additions to the Navy, have a larger proportion of heating surface than former examples, in consequence of the recommendation contained in the 1893 Report of the Admiralty Committee on the designs of machinery for warships. The results as to weight of machinery are briefly as follows :—

EIGHT VESSELS BUILT UNDER NAVAL DEFENCE ACT.

Mean I.H.P. developed.	Average Steam Pressure—Boilers.	Heating Surface per I.H.P. (mean).	Weight in lbs. per I.H.P.	
			Engines.	Boilers.
11500	149	1·7	113	116
9430	150	2·1	146	141
AVERAGE OF TEN BATTLESHIPS BUILT SINCE 1893.				
12414	149	2·0	111	131
10404	148	2·4	132	156
6170	140	4·1	261	486

Eight of these vessels are fitted with forced draught on the closed stokehold system, and two of them with induced draught apparatus, similar to what was originally tried in the "Gossamer," artificial draught being used in all of them for obtaining maximum power.

The I.H.P. developed per ton of machinery is less than in the eight vessels compared with them, but the engines were made rather more substantial, and the additional size of boilers is, of course, also responsible for increased weight.

[1] Min. Proc. Inst., C.E., cxix., pp. 17—46.
[2] Min. Proc. Inst., C.E., cxxxvii., pp. 202—241.

Ten first class Cruisers with triple-expansion engines, having four cylinders and four cranks and with Belleville boilers, give better results. The "Powerful" and "Terrible" with 48 boilers, without economisers, give :—

I.H.P. developed.	Steam Pressure—Boiler.	Heating Surface per I.H.P.	Weights per I.H.P.	
			Engines.	Boilers.
5058	216·5	—	—	—
18479	227·5	3·66	130	140
22547	231·0	3·00	107	115
25774	243·0	2·63	94	100

The I.H.P. per ton of machinery for the three higher powers is 8·29, 10·10, and 11·55. In the "Ariadne," fitted with 30 Belleville boilers with economisers, it is 12·14 for 19,156 I.H.P., with 2·47 square feet of heating surface per I.H.P., and a weight of 91 lbs. per I.H.P. for the boilers and 93 for engines, the steam pressure at boilers having been 288 lbs. per square inch.

In the second class Cruisers fitted with cylindrical boilers we have :—

I.H.P. developed (mean).	Steam pressure—Boiler.	Heating surface per I.H.P.	Weights per I.H.P.	
			Engines.	Boilers.
Forced draught 9846·7	151·0	1·88	84	124
Natural ... ... 8307·8	150·0	2·23	99	148

I.H.P. per ton of machinery at higher power 9·07 : whilst for vessels of the same class, fitted with 18 Belleville boilers of eight elements without economisers, we have :—

I.H.P. developed.	Steam pressure—Boiler.	Heating surface per I.H.P.	Weights per I.H.P.	
			Engines.	Boilers.
10240	265	2·49	82	99

Third class Cruisers and Torpedo-boat Destroyers show similar results, Sir A. J. Durston having said that no difficulty had been experienced in working with a boiler pressure of 300 lbs., and an engine pressure of 250 lbs., and that the influence of increased pressure of steam on the economy of weight and space had been considerable.

Mail Steamers.—In Mail Steamer work, according to Mr. List, the limit of steam pressure with tank boilers has practically been reached. They are using double-ended 8-furnace boilers, 17 ft. mean diameter, and 19 ft. 2 ins. long for a working pressure of 210 lbs. per square inch. The boiler shell plates are $1\frac{21}{32}$ inch thick, and the furnaces are 44 inches internal diameter and $\frac{11}{16}$ inch thick; the steel of the shells having an ultimate tensile strength of between 31 and 34 tons per square inch. The weight of such a boiler, with mountings, is 115 tons, with

TABLE

		Type of Boiler		BELLEVILLE				ORIOLLE		
		Name of Vessel		ALGER	LATOUCHE TRÉVILLE	BUGEAUD	BOUVET	ZOUAVE	TORPEDO-BOATS 161, 162, 163	JEMMAPES
	1	Working pressure at boilers n	lbs. per sq. in.	242	242	242	242	199	199	213
General particulars	2	Grate area, total . G	sq. ft.	754	694	757·6	1,128	62·6	48·4	646
	3	Heating surface, total . S	sq. ft.	22,261	19,526	21,593	32,175	2,196	1,705	21,647
	4	Horse-power developed on trial	F	8,202	8,168	9,440	13,817*	1,000	1,101	9,106
	5	Coal burnt per sq. ft. of grate K	lbs.	18·64	21·21	25·68	27·36*	37·07	58·24	30·1
	6	Coal burnt per horse-power per hour on trial C	lbs.	1·714	1·806	2·06	2·235*	2·331	2·564	2·137
I.—Elements varying with the working pressure and whose weight per square foot of grate ought to be proportional to that pressure.	7	Weight of the body of the boiler without fire-bars or masonry	lbs.	281,420	238,320	246,229	346,357	17,637	17,046	409,904
	8	Stop, safety, blow-off, and reducing valves, separators on steam-pipe, and superheaters	lbs.	100,300	74,146	102,675	114,764	7,716	1,402	37,700
	9	Piping and cocks and valves in stokeholds	lbs.	48,926	29,509	44,092	76,059	2,205	1,074	37,762
	10	Total weights, I. P_1	lbs.	430,646	911,975	392,996	537,180	27,558	19,522	485,366
	11	Ratio.	$\frac{P_1}{G}$	571·1	492·7	519·7	476·7	438·8	403·3	751·4
	12	Ratio	$\frac{P_1}{G\,n}$	2·36	2·04	2·14	1·97	2·2	2·05	3·53
II.—Elements depending on the rate of working, that is to say, on the quantity of coal burnt per square foot of grate, or on the quantity of water evaporated per square foot of grate. The total of these weights per square foot of grate should be proportional to the combustion.	13	Feed-pumps	lbs.	19,440	20,062	26,185	29,489	1,477	2,404	18,560
	14	Feed-water tanks and reserve tanks	lbs.	18,310	9,502	12,588	12,125	661	289	7,502
	15	Feed-water heaters	lbs.	..	..	..	..	..	1,190	..
	16	Filters, water-purifying apparatus, lime-water tanks	lbs.	2,866	7,055	8,673	16,755	331	216	710
	17	Distillers for "make-up"	lbs.	4,850	12,786	6,431	16,534	..	172	9,154
	18	Water in feed and reserve tanks, and in the above-named fittings	lbs.	48,502	37,479	44,202	63,934	1,764	1,764	76,696
	19	Fans for forced or suction draught	lbs.	5,315	15,185	25,353	40,345	487	659	11,153
	20	Apparatus for heating the air	lbs.	..	..	..	..	..	..	..
	21	Total weights, II. P_2	lbs.	94,289	102,069	123,412	179,182	4,720	7,691	123,755
	22	Ratio	$\frac{P_2}{G}$	125	147·1	162·9	158·9	75·2	159	191·6
	23	Ratio.	$\frac{P_2}{G\,K}$	6·71	6·93	6·34	5·81	2·03	2·73	6·37
III.—Elements independent of both n and K, which ought to be directly proportional to the grate area G.	24	Water in boilers	lbs.	45,415	40,036	35,715	65,257	6,173	4,850	110,241
	25	Grates, firebricks, and fire-bridges	lbs.	121,497	99,539	107,951	163,018	5,071	3,119	89,386
	26	Funnels, uptakes and smoke-boxes	lbs.	50,287	42,990	61,377	95,902	1,548	686	37,919
	27	Non-conducting coverings, casings, and lagging of all kinds	lbs.	191,762	129,276	147,981	192,117	783	267	17,637
	28	Tools and spare gear	lbs.	14,870	13,669	15,143	24,251	3,307	390	18,409
	29	Stokehold floors and ladders	lbs.	31,118	19,842	27,970	42,990	1,190	403	19,396
	30	Total weights, III. P_3	lbs.	454,949	343,354	396,137	583,535	18,067	9,735	292,978
	31	Ratio.	$\frac{P_3}{G}$	603·4	497·6	522·9	517·4	287·7	201·2	453·5
Results	32	Total weight $P_1 + P_2 + P_3$	lbs. tons	979,884 437·5	789,398 352·5	912,545 407·39	1,299,897 580·38	50,345 22·48	36,951 16·5	902,099 402·78
	33	Total weight per sq. ft. of grate . $A = \frac{P_1 + P_2 + P_3}{G}$	lbs.	1299·6	1137·3	1204·6	1152·4	801·7	763·5	1396·4
	34	Horse-power developed on trial per sq. ft. of grate. $B = \frac{F}{G}$		10·88	11·77	12·46	12·25	15·92	22·75	14·10
	35	Total weight per horse-power $D = \frac{P_1 + P_2 + P_3}{F} = \frac{A\,C}{K}$	lbs.	119·5	96·7	96·7	94·1	50·2	33·6	99·1

$49\frac{1}{4}$ tons additional for water. In a comparative estimate of Belleville boilers suitable for the same work, but at 300 lbs. pressure, it appeared that they would have $4\frac{1}{2}$ per cent. less total heating surface than the tank boilers; they would weigh 40 per cent. less, and save in length of space 13 per cent., but would cost 50 per cent. more in first cost.

Boilers in French Navy.—In the French Navy several vessels have been fitted with water-tube boilers, the designs chosen being those of the *Belleville, Oriolle, D'Allest, Niclausse, Du Temple, Du Temple-Guyot, Normand, Normand-Sigaudy,* and *Thornycroft* boilers. A comparative view of these is given in Table CIII., taken from M. Bertin's work on "Marine Boilers,"[1] from which much interesting information may be obtained on this subject:

[1] English Translation by Mr. L. S. Robinson (London. John Murray, 1898).

CIII.

D'ALLEST				NICLAUSSE.	DU TEMPLE.			NORMAND		NORMAND-SIGAUDY.	DU TEMPLE-GUYOT.	THORNYCROFT.	
CHASSELOUP-LAUBAT.	CASSINI.	CARNOT.	DU CHAYLA.	FRIANT	DRAGON. GRENADIER. LANCIER.	AVERNE. DAUPHIN.	FLIBUSTIER. ARIEL. (Du Temple-Normand.)	TORPEDO-BOATS 144, 149, 162, 163	TORPEDO-BOATS 183 TO 186.	CHÂTEAU-RENAULT.	JEANNE-D'ARC.	VÉLOCE.	
213	213	213	213	213	171	190	190	190	190	213	256	199	1
738	844	1,076	732	783	81·4	76·4	66·7	35·7	36·7	1,362	2043·2	76	2
10,458	10,667	37,201	23,530	23,340	3,097	2,682	3,098	1,894	1,839	64,130	76,273	6,128	3
9,833	5,521	14,003*	9,376*	9,488	1,845	2,181	2,364	1,176	1,809	23,700	28,130	..	4
23·66	31·27	30·72	30·72	24·53	46·74	61·06	63·41	67·85	68·11	30·7	34·3	61·44	5
1·779	1·949	2·235	2·391	2·036	2·025	2·130	1·638	1·961	1·85	1·84	2·009	..	6
305,752	172,664	520,511	302,470	406,034	29,941	25,572	36,137	17,019	19,467	600,970	878,200	31,716	7
92,077	24,319	26,456	22,016	378						44,092	68,501	1,610	8
41,028	17,619	97,003	74,064	41,204	6,089	6,048	3,778	986	909	111,330	130,360	2,976	9
378,857	214,602	643,960	399,470	447,681	29,930	29,615	37,915	18,805	20,466	736,392	1,057,651	36,092	10
517·8	624	506·5	345·7	371·7	490·8	387·5	566·5	326·8	320·8	355·36	643·5	476·1	11
2·43	2·90	2·81	2·56	2·66	2·67	1·96	2·20*	2·65	2·60	3·61	3·41	2·20	12
11,404	20,944	23,795	9,480	14,143	372	719	671	287	309	27,557	20,865	On Main Engines	13
9,080	4,101	12,228	9,259	11,094	344	1,457	342	456	320	20,064	12,228	329	14
	...	3,205		..	1,640	1,870	1,640	654	1,071	20,504	..	..	15
3,907	2,502	4,080	2,866	1,076	..	467	.	..	..	17,637	26,455	441	16
8,431	4,319	13,846	8,598	9,124	345	349	343	163	238	26,014	28,600	..	17
21,495	3,069	46,297	63,060	59,370	4,430	4,343	3,009	1,764	1,874	101,416	130,070	3,197	18
10,760	3,331	14,992	10,141	10,200	485	657	970	508	485	30,064	30,863	666	19
													20
62,017	65,466	116,948	73,413	101,673	7,705	9,771	6,775	4,217	4,312	234,850	360,145	44,833	21
85·3	126·4	110·8	100·8	135·7	94·06	127·9	101·6	118·1	111·4	187·11	138·1	83·6	22
3·48	4·04	3·5	3·27	6·45	1·94	2·1	1·6	1·74	1·64	6·00	4·62	1·03	23
110,049	59,966	181,961	116,850	101,413	4,180	5,910	9,435	3,952	3,952	194,000	198,410	3,406	24
76,223	43,973	160,937	114,640	72,753	4,961	3,551	5,269	2,831	2,996	226,190	181,320	6,195	25
148,669	19,991	133,159	83,672	61,569	1,102	2,954	1,102	673	970	209,440	189,600	1,023	26
7,134	10,538	22,046	15,432	..	1,907	959	2,354	500	556	31,967	37,476	310	27
16,682	7,332	24,251	15,433	16,535	441	595	992	617	441	42,769	44,092	3,310	28
28,711	6,993	39,683	30,864	13,960	1,102	660	1,102	236	235	61,729	57,320	476	29
394,488	180,792	561,737	375,890	261,249	13,702	16,849	30,654	11,043	11,252	766,095	706,220	19,910	30
538·9	488·3	522·1	513·5	333·6	166·3	220·4	312·7	300·5	290·2	362·48	430·4	262	31
835,962 278·28	409,060 182·62	1,221,649 501·45	845,773 376·98	818,553 363·19	61,337 27·38	56,225 25·1	65,344 29·26	34,071 13·21	36,030 16·085	1,777,337 793·4	2,026,014 904·5	60,775 27·14	32
1142	1189·(	1261·1	1159·6	1039	758·6	735·9	282·6	951·6	891	1,089·05	1,201·4	720·6	33
13·48	15·03	12·76	12·61	13·06	23·67	20·55	28·71	32·94	41·32	16·67	17·16	..	34
85·0	74·1	90·3	90·5	96·2	28·3	25·8	25·4	30	23·3	78·20	72·09	..	35

*From designer's calculations.

(To face p. 564.)

D'Allest Boiler.—Trials with the D'Allest boilers gave the following results :—

TABLE CIV.

Vessels.	Bombe.	Cassini.	Chasseloup-Laubat.	Jemmapes.
COAL CONSUMPTION TRIALS.				
Boiler pressure, lbs. per sq. in.	125·0	163·5	171·5	159·3
Pressure at reducing valve ...	114·61	151·05	135·58	166·98
Expansions $\Delta = \frac{D^2}{i\,d^2}$	4·39	8·6	12·59	11·86
Lbs. coal consumed :—				
Per sq. ft. of grate ...	21·074	20·115	10·85	14·715
Per H.P. hour	2·092	1·817	1·48	2·0
SPEED TRIALS.				
Boiler pressure, lbs. per sq. in.	139·74	195·57	184·9	203·82
Pressure at reducing valve ...	119·474	171·95	159·88	184·88
Expansions $\Delta = \frac{D^2}{i\,d^2}$	3·78	6·84	7·34	8·763
Lbs. coal consumed :—				
Per sq. ft. of grate ...	48·25	31·273	23·88	30·122
Per H.P. hour	2·374	1·947	1·779	2·101

Niclausse Boiler.—Trials with the Niclausse boiler on board the warship, "Friant," with careful and regular stoking gave the following results :—

COAL CONSUMPTION TRIALS.

Boiler presure, lbs. per sq. inch	180
Pressure at reducing valves, lbs, per sq. inch ...	141·6
Number of expansions in engines, $\Delta = \frac{D^2}{i d^2}$ ...	12.40
Coal burned per sq. ft. of grate, lbs.	10·25
Coal burned per H.P. hour	1·49

SPEED TRIALS.

Boiler pressure, lbs. per sq. inch	194·57
Pressure at reducing valves, lbs. per sq. inch ...	163·14
Number of expansions $= \frac{D^2}{i d^2}$	7·63
Coal burned per sq. ft. of grate, lbs.	25·03
Coal burned per H.P. hour	2·032

It is stated, by M. Bertin, that a boiler in the works of M. Niclausse, under forced firing has shewn a rate of evaporation equal to 72 lbs. of water per square foot of heating surface, without injury to the tubes, although the chimney was burnt through. These experiments were designed to prove the indestructibility of the boiler, apart from any expectation of obtaining economy of steam generation.

In trials of the Niclausse boilers of the torpedo-boat "Temeraire," on shore in 1897, rates of evaporation of 11·25, 10·12, 10·72, and 10·3 lbs. of water from and at 212° Fah. per lb. of coal were obtained with draught pressures of 1·1, 1·5. 2·7 and 4·3 inches of water respectively, the rates of combustion having been 41, 51·2, 66·5 and 81·7 lbs. of coal per square foot of grate. The evaporation in lbs. of steam per square foot of heating surface is stated as having been for these rates of combustion 4.6, 10·6, 13·2, and 15·9 lbs.

The following figure shows these results plotted in curves.

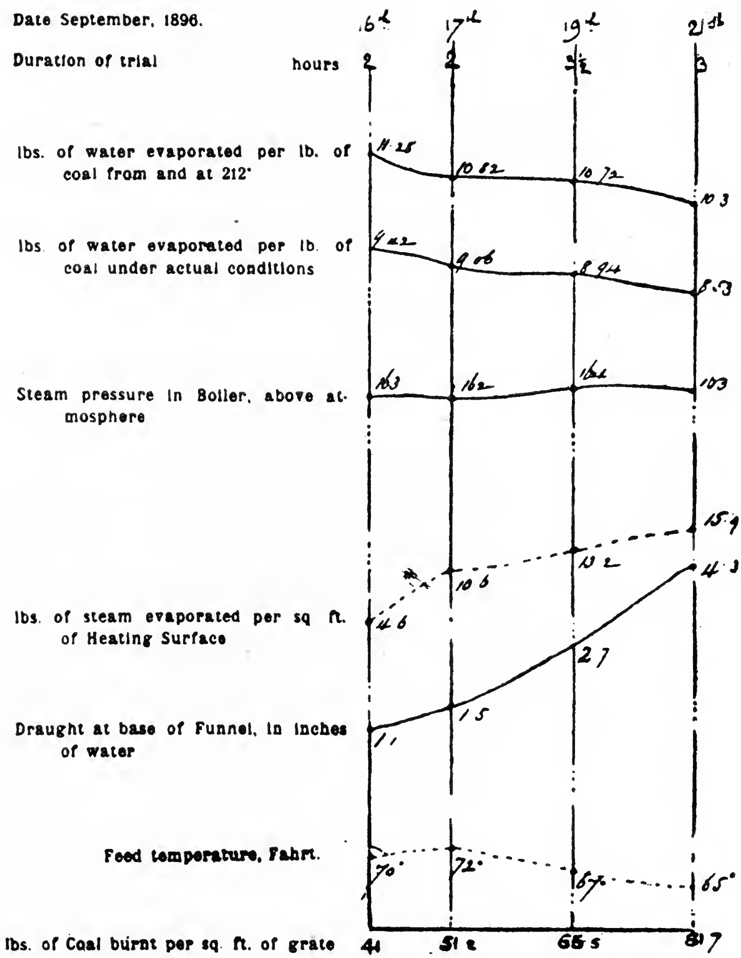


FIG. 312.

Further results with Niclausse boilers are given by Mr. Mark Robinson in Trans. Inst. N.A., Vol. 37, pp. 119—134, and by M. E. Duchesne in "Quelques Resultats d'essais de Chaudières Militaires Marines" (Mem. et Compt. Rendu de la Soc. des Ingenieures Civils, January, 1898, pp. 54—69).

From the former the following results are taken :—

TABLE CV.

TRIAL OF A NICLAUSSE BOILER AT MESSRS. HUMPHRYS, TENNANT AND Co. HEATING SURFACE 630 SQUARE FEET. GRATE AREA, 19·2 SQUARE FEET.

Date of Trial, 1895.	Duration. Hours.	Steam Pressure. Lbs. per sq. in.	Temperature of Feed. deg. Fah.	Coal burnt per hour. Lbs.	Coal per hour per square foot of grate. Lbs.	Water evaporated per hour. From feed temperature. Lbs.	Water evaporated per hour. From and at 212 deg. Lbs.	Water per lb. of coal. From feed temperature. Lbs.	Water per lb. of coal. From and at 212 deg. Lbs.
March 15	8	165·4	71·30	364	18·96	3368·89	4030·81	9·25	11·06
March 20	8	171·0	61·40	248¼	12·94	2307·63	2789·08	9·28	11·20
March 25	4	171·5	58·20	672	35·0	5329·73	6454·21	7·93	9·59
March 29	8	169·3	69·50	560	29·2	4630·92	5552·31	8·27	9·90
April 5	8	170·8	60·40	486	25·31	4212·83	5091·59	8·6	10·45

The following figure shows these results in graphic form, arranged in the order of the rates of evaporation.

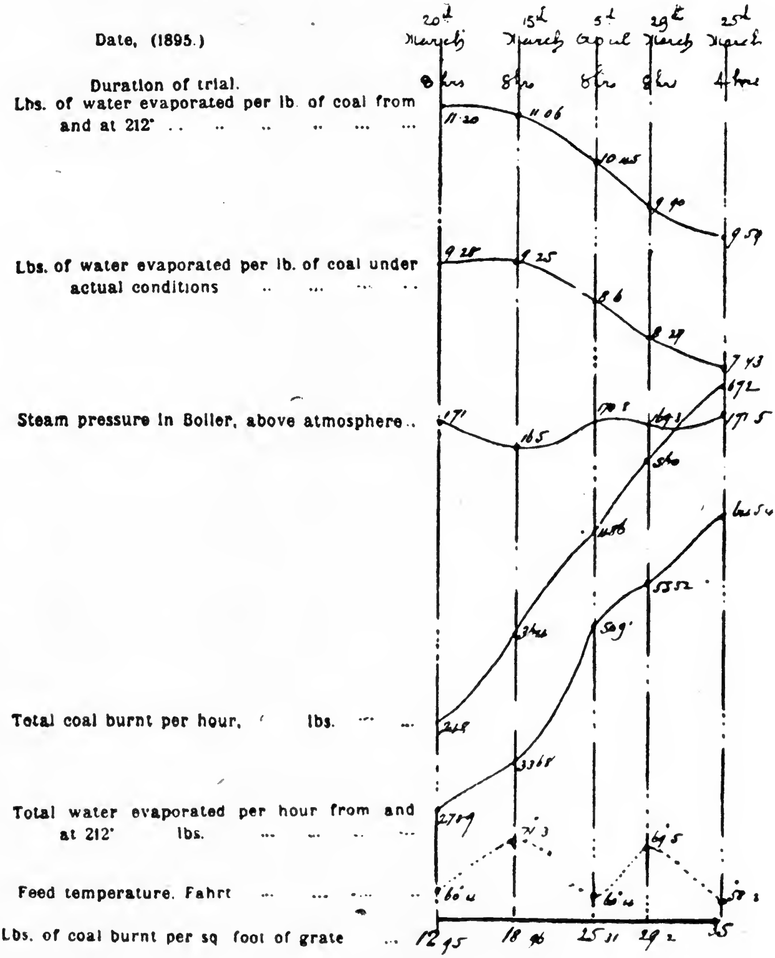


FIG. 313.

Professors Kennedy and W. C. Unwin conducted trials of a Niclausse boiler at Thames Ditton in 1894, and their report is attached to Mr. Robinson's paper. The outer tubes of the boiler were 3·22ins. diameter and 7 feet long; the inner tubes

were 1·5ins. diameter and nearly the same length. The total external tube surface in the boiler was 649 square feet. The trial of 12th May was specially to ascertain how far the boiler could be forced without appreciable priming taking place. The tests showed that the priming on all the trials was practically negligible in amount. The following Table gives the results of the three trials :—

TABLE CVI.

	Date of Trials, 1894.		
	April 10.	April 11.	May 12.
Duration of trial ... ... hours	7·27	7·40	2·95
Barometer (mean)... ... ins.	30·14	29·94	30·09
Total water evaporated ... lbs.	16,000	16,000	12,134
Total coal burnt ... ... „	1,845	1,841	1,422
Carbon value of coal used ...	0·956	0·956	—
Total feed water per lb. of coal lbs.	8·67	8·69	8·53
Total feed water per lb. of coal from and at 212° F. ... lbs.	10·47	10·50	10·34
Total feed water per lb. of carbon value from and at 212° F. lbs.	10·95	10·98	10·82
Coal burnt per sq. ft. grate surface per hour	13·5	13·3	25·6
Feed water per sq. ft. heating surface	3·39	3·33	6·34
Feed water per cubic foot of boiler and boiler-setting per hour ...	2·61	2·57	4·88
Mean steam pressure above atmosphere, lbs. per sq. in. ...	158·6	159·6	144·3
Mean steam pressure absolute, lbs. per sq. in.	173·4	174·3	159·1
Mean temperature of feed water, deg. F.	60·3	60·3	55·0
Mean temperature of air, deg. F. ...	67·4	67·6	62·3
Mean temperature of chimney gases, deg. F.	511·7	502·7	732·0

The moisture in steam was determined for the first two trials by a wire-drawing calorimeter, and was found to be a mean of 1.1 per cent. for the first, and 1·0 per cent. for the second trial.

The figures for utilisation of the heat in each pound of coal, based upon an estimated thermal value for the coal of 13860 heat units as calculated from an ordinary analysis, or from calorimeter experiment, are given in the following Table :—

TABLE CVII.

	April 10.		April 11.	
	Thermal Units.	Percentages.	Thermal Units.	Percentages.
Heat utilised in formation of steam	10,110	72·94	10,136	73·11
Heat lost by imperfect combustion (formation of carbonic oxide)	501	3·61	185	1·33
Heat lost by carbon left in ash.	133	0·96	136	0·98
Heat carried away by waste gases	2,327	16·79	2,435	17·56
Heat lost by radiation and otherwise unaccounted for ...	789	5·70	968	7·02
Thermal value of coal as determined by experiment ...	13,860	100·00	13,860	100·00

In the trial of May 12, the heat utilised in steam formation amounted to 9970 units or 71·9 per cent.

In M. Duchesne's paper it is stated that the Niclausse boilers of the "Menhir" worked for 7000 hours without requiring to be cleaned; and that those of the "Friant" have worked with a consumption of 176 kilogrammes coal per metre carré of grate surface per hour without difficulty for four consecutive hours, and without showing flame at the chimneys. The rates of evaporation at different rates of combustion of coal were ascertained to be as follows :—

Kilogrammes of coal burned per metre carré grate surface per hour (ash included) :—

100	150	200	250	300	350	400

Kilogrammes water evaporated per unit of coal at these rates (water and steam reduced to 100° C.)

11·850	10·860	9·914	9·339	8·734	8·214	7·500

These evaporative trials were continued during four hours. Trials at a rate of combustion of 400 kilogrammes coal per metre carré grate surface per hour were made and continued for ten hours, the air pressure being 20 mm., without damage. The diameter of the tubes was 40 mm., and tubes of 82 mm. have stood the same test.

A careful record of the performances of the tubulous boilers in the French Navy prior to 1895, and a trenchant criticism of various features of their construction and working at that time, will be found in a paper by Mr. John K. Robison, Assistant Engineer in the U.S. Navy, read before the American Society of Naval Engineers and published in their journal, from which it was republished in *Engineering*, Vol. lx., pp. 555, 587, 617, 682 and 749. Mr. Robison indicates the good and bad qualities of Belleville, Lagrafel or D'Allest and Niclausse boilers, and evidently thinks more highly of the two latter than of the former.

Of trials of water-tube boilers in the German Navy there are no accounts published in English, but articles on that subject have appeared in the *Zeitschrift des Vereines Deutscher Ingenieure* of 11th and 18th September, 1897 ("Versuche in der Deutschen Kriegsmarine mit Wasserrohrkesseln"), and on the Buttner Water-tube Boiler in *La Revue Technique* of 10th September, 1897.

Mosher Boiler.—A Mosher boiler gave the following results on an eight-hours trial with natural draught with Pocahontas semi-bituminous coal.

Coal per square foot of grate per hour	7·1 lbs.
Water evaporated per lb. of coal	9·12 lbs.
Air supplied per lb. of coal	304 cub. ft.
Temperature of gases at base of funnel	442° Fahr.
Draught at base of funnel	3 in.
Wetness of steam as measured by calorimeter	1·5 per cent.
Percentage of ashes	7 per cent.
Quantity of water evaporated in ash-pit during the whole trial	90·2 lbs.

The principal dimensions of the boiler were :—

Grate area	33 sq. ft.
Heating surface	1108 „
Ratio of grate to heating surface ...	33·6
Load on safety valve	185 lbs. p. sq. in.

The heat utilisation was as follows :—

Heat utilised in evaporating water	...	76·0 per cent.
Heat lost in the funnel ...	...	13·0 ,,
Heat lost in radiation ...	...	9·1 ,,
Heat lost in cinders and evaporation of water in the ashpan ...	...	1·0 ,,
Total heat of combustion	...	100·0

"Clyde" Boiler.—The following are the results of trials of three boilers of Messrs. *Fleming and Ferguson's* design :—

TABLE CVIII.

	No. 1.	No. 2.	No. 3.
Grate area	$9\frac{1}{2}$ sq. ft.	20 sq. ft.	45·8 sq. ft.
Heating surface	540 sq. ft.	630 sq. ft.	1,650 sq. ft.
Coal consumed per square foot of grate per hour	24·8 lb.	20·3 lb.	30·3 lb.
Total coal consumed per hour ...	236 lb.	406 lb.	1,391 lb.
Water evaporated per hour... ...	2,040 lb.	3,500 lb.	9,812 lb.
Water evaporated per hour from and at 212° F.	2,468 lb.	4,260 lb.	11,345 lb.
Water evaporated per lb. of coal from and at 212° F.	10·43 lb.	10·5 lb.	8·15 lb.
Water evaporated per lb. of combustible	11·15 lb.	11·25 lb.	8·7 lb.
Water evaporated per square foot of grate per hour	260 lb.	213 lb.	247 lb.
Water evaporated per square foot of heating surface per hour from and at 212° F.	4·5 lb.	6·7 lb.	6·8 lb.
Quality of coal used	Welsh	Welsh	Scotch
Draught natural on all trials.			

This boiler is fitted in the s.s. "Aberdeen," a vessel owned by the Canadian Government, and has given satisfaction. The generating tubes are $2\frac{1}{2}$ inches diameter, the steam cylinder being of sufficient diameter to permit of their being wholly withdrawn into it when any tubes require to be replaced.

The following are the proportions of three different sizes and arrangements of the tubes and chambers proposed by Messrs. Fleming and Ferguson :—

	Boiler with 3 furnaces.	Boiler with 6 furnaces (double-ended).	Boiler with 4 transverse furnaces.
Grate area, square ft.	50	138	165
Heating surface, square ft.	1450·5	4801	5000
Ratio of heating surface to grate ...	28·98	34·79	30·3
Total weight with water but without funnel, tons	30	75	110
Working pressure, lbs. per sq. in....	220	200	250

Mumford's Boiler.—Mumford's water-tube boilers have given satisfactory results in the trials on H.M.S. "Salamander." This vessel is of the same type as the "Sharpshooter," the first fitted with the Belleville boiler, and since then the class has been utilised for trying various systems of tubulous generators, the Babcock and Wilcox, Niclausse, and the Du Temple, as well as the Mumford. The boilers on an eight-hours' natural draught trial gave sufficient steam for 2575 I.H.P., and although they were only required to give 3500 I.H.P. under forced draught, the power was actually 4114 I.H.P., which was got with 2·6 inches of air pressure in the stokehold. The boilers, of which there are four, have 180 square feet of grate area and 8000 square feet of heating surface, so that the power is equal to a little over 23 horse-power per square foot of grate, while there was barely two square feet of heating surface for each unit of power developed, both results being very good, even for an express boiler.

Haythorn Boiler.—Of other water-tube boilers which have been fitted in steamers, the *Haythorn* boiler is one of considerable promise, judged from the results of trials which have been made. The first of these boilers was made and tried as a land boiler, of which an illustration will be found in *Engineering*, Vol. lx., p. 680.

The heating surface of the boiler was 430 square feet, and the grate area 6·8 square feet, the ratio between these two being 63 to 1.

The following are the results of the trials :—

TABLE CIX.

Date of trial, 1895	April 11.	April 30.	May 1.	May 2.	May 30.	June 12.	June 14.	June 14.
Chimney draught by water gauge ins.	0·15	$\frac{5}{16}$	·134	$\frac{3}{16}$	·24	$\frac{1}{2}$	$\frac{3}{8}$	$\frac{3}{8}$
Air pressure under fire, forced draught	—	—	—	—	2	$2\frac{1}{2}$	$2\frac{11}{16}$	$2\frac{1}{2}$
Air temperature, Fah.	55	58·4	57	60	80	63	60	60·6
Mean feed temperature, Fah.	$52\frac{1}{2}$	51·5	47·7	47·2	52	56·5	55·5	55·5
Coal consumed per hour, lbs.	100	120·6	68	102·6	$271\frac{1}{4}$	338.3	458·3	504
Coal consumed per hour, per sq. ft. of grate, lbs. ...	14·7	17·64	10	15·1	39·8	49·8	67·4	74·1
Water evaporated per hour, lbs.	911	979·2	556·8	909	2565	2757	3386	3648
Water evaporated per hour per lb. of coal used ...	9·11	8·2	8·6	8·86	9·45	8·15	7·39	7·24
Equivalent evaporation from and at 212°, lbs. ...	11·1	9·97	10·5	10·86	11·6	9·94	9·04	8·9
Coal consumed per hour per sq. ft. heating surface	0·23	0·28	0·16	0·238	0·63	0·8	1·07	1·17
Water evaporated per hour per sq. ft. heating surface	2·58	2·78	1·6	2·6	6	6·4	7·9	8·48
Mean steam pressure, lbs. per sq. in.	147	157	163·2	195·6	240	233	250	251
Corresponding steam temperature, Fah.	364	369	372	385·7	402	400	405	405
Mean temperature of escaping gases, Fah.	460	527	382	478	685	677	770	799
Quality of steam	dry	dry	dry	dry	dry	dry	dry	dry

Subsequently two boilers were fitted in the paddle steamer "Meg Merrilies," the following being the dimensions of each :—

Diameter of tubes, 2 ins. and $3\frac{1}{8}$ ins., reduced to 2 ins.
Pitch of tubes, $3\frac{1}{4}$ ins. by $3\frac{1}{4}$ ins.
Longest tube, 14 ft. 3 ins. between ferrules.
Shortest tube, 9 ft. 1 in. between ferrules.
Mean tube, 11 ft. 8 ins. between ferrules.
Number of 2 in. tubes in boiler, 216.
Numbes of $3\frac{1}{8}$ in. tubes in boiler, 54.
Total number of tubes, 270.
Number of tubes in each element, 30 ; number of elements, 9.
Effective heating surface of tubes in one element, 191·3 sq. ft.
Total heating surface of tubes in boiler, 1721·7 sq. ft.
Total grate surface in one boiler, 30·5 sq. ft.
Ratio of heating to grate surface, 56·4 to 1 sq. ft.
Weight of one element, excluding water, 13 cwts.
Weight of one boiler, excluding water, 13·2 tons.
Weight of water in one boiler, 2·35 tons.
Total weight of boiler, including water, 15·55 tons.
Working steam pressure, 200 lbs. per square inch.

The results of a trial, lasting for six hours, of these boilers on board the steamer while cruising in the Firth of Clyde on 21st December, 1898, are given in the following tabular statement :—

TABLE CX.

EVAPORATIVE TEST OF THE HAYTHORN WATER-TUBE BOILERS OF P.S. "MEG MERRILIES."

BOILERS. (*Two Haythorn Water-Tube Boilers.*)	
Total heating surface	3444 square feet.
Total grate area	61 "
Ratio $\frac{\text{Heating surface}}{\text{Grate area}}$	56·4 "
Mean steam pressure above atmosphere	186 lbs.
TEMPERATURES.	
Mean funnel temperature, about	600°
Mean temperature of stokehold	68°
Mean temperature of feed water	127·4°
DRAUGHT.	
Mean funnel draught below atmosphere	·35" water.
Mean air pressure in stokehold above atmosphere	·55" "
Total	·9" "

TABLE CX. *continued.*

COAL.—Quality, Welsh.

Analysis—

Carbon ...	83·63 per cent.
Hydrogen	3·70 „
Oxygen ...	4·48 „
Nitrogen	·99 „
Sulphur ...	·7 „
Water ...	1·28 „
Ashes ...	5·22 „

Theoretical evaporative power 14·5 lbs. water from and at 212°.

ANALYSIS OF SMOKE.—*Mean of Three Samples.*

	By Volume.	By Weight.
Carbonic acid ...	8·17	12·1
Carbonic oxide	·1	·09
Hydrocarbons ...	...	...
Oxygen ...	10·3	11·03
Nitrogen	81·43	76·78
	100·00	100·00

COAL.

Total used in 6 hours 3 minutes	9321 lbs.
Used per hour ...	1541 „
„ per square foot of grate ...	25·26 „
„ „ of heating surface ...	·447 „

ASHES.

Total ashes for 6 hours 3 minutes ...	95 lbs.
„ clinker for 6 hours 3 minutes ...	482 „
Total ...	577 „
Ashes and clinker per hour ...	95 „
„ percentage of coal ...	6·2 per cent.

WATER.—*Measured for* 5 *hours* 47 *minutes* 11 *seconds.*

Total quantity from hotwell ...	80943 lbs.
Supplementary from tanks ...	2133 „
Total ...	83076 „
Water per hour ...	14345 „
„ „ per square foot grate ...	235 „
„ „ „ heating surface ...	4·165 „
Water evaporated per lb. of coal from temperature of feed water ...	9·309 „
Water evaporated per lb. of coal from and at 212°	10·62 „

An independent dry steam test was made by means of a "Barrus" Wire-drawing Calorimeter. This test gave the mean dryness factor at ·924, or only 2·6 per cent. of water in the steam.

From above results the efficiency of these boilers is—

$$\frac{\text{Actual evaporative power per lb. of coal from and at } 212^\circ}{\text{Theoretical evaporative power of coal from and at } 212^\circ} = \frac{10{\cdot}62}{14{\cdot}5} = 73{\cdot}2 \text{ per cent.}$$

Also water evaporated per lb. of carbon value from and at 212° 11·06 lbs.

The three boilers fitted in the paddle steamer "Lorna Doone" in May, 1899, had some slight improvements in detail, such as the formation of a combustion space by means of an extra row of tubes between the grate and the main body of the boiler tubes.

The following are their principal dimensions :—

Diameter of tubes, 2 ins. and $3\frac{1}{8}$ ins., reduced to $2\frac{1}{8}$ ins.
Pitch of tubes, $3\frac{1}{4}$ ins. by $3\frac{1}{4}$ ins.
Longest tube, 14 ft. 6 ins. between ferrules.
Shortest tube, 8 ft. 4 in. between ferrules.
Mean tube, 11 ft. 5 in. between ferrules.
Number of 2 in. tubes in one boiler, 264.
Number of $3\frac{1}{8}$ in. tubes in one boiler, 96.
Total number of tubes in one boiler, 360.
Number of tubes in one element, 30 ; number of elements, 12.
Effective heating surface of tubes in one element, 200 sq. ft.
Total heating surface of tubes in one boiler, 2,400 sq. ft.
Total grate surface in one boiler, 42·4 sq. ft.
Ratio of heating to grate surface, 56·6 to 1 sq. ft.
Weight of one element, excluding water, 14 cwts.
Weight of one boiler, excluding water, 18·6 tons.
Weight of water in one boiler, 2·8 tons.
Total weight of boiler, including water, 21·5 tons.
Working steam pressure, 160 lbs. per sq. inch.

On trial these boilers gave the following results :—

TABLE CXI.

P. S. "LORNA DOONE" OF THE SOUTHAMPTON, ISLE OF WIGHT, AND SOUTH OF ENGLAND R. M. S. P. COY.

Date of Voyage.	Total Distance Travelled.	Duration of Voyage.	Weights on board.	Average I. H. P. Developed.	Quality of Coal used.	Coal used per mile run.	Coal used per hour with engines running.	Total coal used in 24 hours.	Lbs. of Coal per I. H. P.	Type of Boiler used.
22nd Aug., 1899	170 knots	H. M. S. 12 33 10	Coal ......22 tons Water in Tanks. 5 „ Passsengers ...35 „ Total 62 „	1,411	Inferior.	204 lbs. gross *i.e.* including banking of fire.	Ton cwt. qr. lb. 1 4 3 7 Coal for banking not taken.	Ton cwt. qr. lbs. 15 10 0 11	1·96	Haythorn water-tube.

Some very instructive trials to determine the relative value for evaporation of successive tiers of tubes from the bottom row upwards in such boilers as the Niclausse, and the advantage to be gained by adding heating surface, either in rows of boiler tubes or in economisers, were carried out by Messrs. Niclausse in Paris. They constructed a special boiler containing 12 rows of tubes, two in each row, placed side by side. Each row delivered its steam separately, and was separately supplied with water of measured quantity. The tests were carried out at rates of combustion varying from 10lbs. up to 61lbs. per square foot of grate, and the proportionate evaporation in each row of tubes was maintained almost exactly at all the different rates of combustion. The lowest row, directly over the fire, evaporated nearly one quarter of the whole, and the first three rows, having 7·5 square feet of heating surface to one square foot of grate, evaporated nearly one half. (See pp. 187—191 *ante*).

The first six rows, with a surface ratio of fifteen to one, evaporated nearly two-thirds of the whole. The last, or uppermost row evaporated about 3¾ per cent., and the law of decreasing efficiency under the conditions of the trials was readily deducible, enabling the value of any additional surface to be estimated.

TWO TESTS OF SIMPSON AND BODMAN'S FLASH BOILER.

Particulars of Generator.

Weight of generator, 645 lbs.
Weight of regulating drum, 98 lbs.
Number of members, 12.
Tubes per member, 2.
Length indented per tube, 2ft. 6in.
Pitch of indent, 3½ in.
Heating surface indented, 46 square feet.
Joints, the " Haythorn " differential joint.
Hydraulic (cold) test for joints, 750 lbs. per square inch.
Thermometer used, Mercury, with nitrogen chamber reaching to 900° Fah., bulb depending 1ft. 6in. into drum.
Grate area, 2¾ square feet.
Fire bars, ½-in. wide ; air spaces, ½-in. wide.

Lighting Up Test.

Fire made up from plain kindling wood and 7′0 seam coal.
Fire lit at 3.30 p.m.
Steam for blower at 3.40 p.m.
400° Fah. in drum at 3.55 p.m.
Ready for work at 4 p.m.

Table CXII.

FIRST TEST. DURATION THREE HOURS.

Fuel Used—Furness Coke.

Starting.—Fire lit and boiler blown out for one hour, the fire then drawn out and thrown aside. Temperature of boiler taken—380° Fah.—fresh firing applied, and test proceeded with.

	1st Hour.			2nd Hour.			3rd Hour.		
	H.M.	Deg. Fah.	lbs.	H.M.	Deg. Fah.	lbs.	H.M.	Deg. Fah.	lbs.
Times of stoking and temperature at each stoking taken before fire door is opened	11.25	380°		12.25	500°		1.25	500°	
	11.35	600°		12.35	600°		1.37	600°	
	11.45	730°		12.45	730°		1.45	650°	
	11.55	500°		12.55	500°		1.55	700°	
	12. 5	500°		1. 5	500°		2. 5	730°	
	12.15	500°		1.15	550°		2.15	600°	
Times of clinkering, cleaning, etc.				1.25					
Fuel weighed out at start ...			57			64			78
" " in at finish ...			—			—			—
" used			57			64			78
Gross weight water and tank at start			500			488			412
Gross weight water and tank at finish			234			136			36
Weight of water evaporated ...			266			352			376
Pressure worked at per square inch			100			100			100
Temperature of feed water ...		70°			70°			70°	
Evaporation per lb. fuel used...			4·66			5·5			4·82
" per square foot heating surface			5·78			7·65			8·17
Combustion per square foot grate			20·7			23·27			28·36
Average temperature		535°			563°			630°	
Degrees of superheat above saturation		197°			225°			292°	

Water pumped through at 2.25 to reduce temperature to 380°.
Remarks :—Weight of ash not taken, being very slight.
Nozzle in blast pipe ¼″ diameter.
Evaporation per lb. fuel is taken as shown at pressure and temperature.

Table CXIII.

SECOND TEST. DURATION THREE HOURS.

Fuel—Anthracite.

Starting as in Test I. Temperature 550° Fah.

	1st Hour.			2nd Hour.			3rd Hour.		
	H.M.	Fah.	lbs.	H.M.	Fah.	lbs.	H.M.	Fah.	lbs.
Times of stoking and temperature	9.40	550°		10.40	500°		11.55	450°	
	9.50	780°		10.45	450°		12. 0	550°	
	10. 0	550°		10.50	450°		12. 5	700°	
	10. 5	480°		10.55	500°		12.15	700°	
	10.10	560°		11. 0	510°		12.25	550°	
	10.15	560°		11. 5	375°		12.35	530°	
	10.20	460°		11.10	400°		12.45	530°	
	10.25	460°		11.15	500°				
	10.30	460°		11.20	550°				
	10.35	460°		11.25	550°				
				11.30	550°				
Times of clinkering and cleaning	10.40			11. 5 11.40					
Fuel weighed out at start ...			131			136			69
" " in at finish ...			53			69			—
" used			78			67			69
Weight of Ash			30			30			30
Nett fuel consumed			48			37			39
Gross weight of water and tank at start...			468			500			500
Gross weight of water and tank at finish			126			189			196
Weight of water evaporated ...			342			311			304
Pressure worked at per square inch			100			100			100
Evaporation per nett lb. fuel used			7·12			8·2			7·97
Evaporation per square foot heating surface			7· 0			6·7			6· 6
Combustion per square foot grate			17· 5			13·3			14· 2
Average temperature		532°			485°			572°	
Degrees of superheat above saturation		194°			147°			234°	

Remarks:—The fire bars were evidently not suitable for burning Anthracite, as the amount of ash is excessive.

The bars also choked up badly. Nozzle in flue ¼″ diameter.

Comparison of Results.—It is much to be regretted that there are no reports extant of the work performed by such boilers as those of the highly interesting class introduced early in last century in connection with road vehicles, and also by some of later date, such as the boilers of Dr. De Laval in Sweden, and one or two others. A comparison of results would be of great use in determining the relative value of different arrangements of heating surface and other elements of boiler design, as worked under ordinary conditions of steam-raising. As we have pointed out in Chap. IV., the value of experiments made to determine the capacity of metal surfaces for heat transmission has been greatly interfered with by reason of the actual design of the apparatus used. Hence such calculations as those of M. Bertin (in "Marine Boilers," pp. 126-129) which are founded upon the formula deduced from Mr. Blechynden's experiments cannot be relied upon for any general application. Enquiry into the results actually obtained in lbs. of water evaporated per square foot of heating surface in various boilers, only shows that these results are not concordant, and that therefore we have not arrived at the time when a rule or formula can with safety be deduced. For instance, many Babcock and Wilcox land boilers show an evaporation of not more than 2·7 lbs. of water per square foot of heating surface per hour; in the diagram of boiler trials at Philadelphia in 1876 (p. 527 ante) only five out of thirteen boilers show an evaporation above the average of 2·86 lbs. per square foot of heating surface; one of these five, however, showed 10·585 lbs. A "Glasgow" water-tube boiler has shown 6lbs. per square foot of heating surface per hour, and instances of other boilers giving figures of from 1·7 up to 20·05 lbs. will be found in this chapter. The latter figure was credited to locomotive boilers in Italian torpedo boats, but it has been reached on special forcing trials with either Yarrow or Thornycroft forms of water tube-boilers. The Niclausse boiler of the "Temeraire" showed from 4·5 to 15·9 lbs. on trial. The special boiler designed by Simpson and Bodman for motor-car work gave on trial an evaporative rate of 9lbs. per square foot of heating surface, and the boiler of De Laval seems to have done more than this. Professor Watkinson announced a result of 50lbs. of water evaporated per hour per square foot of surface in an experimental boiler of new design; and we have the figure of 72lbs. as previously given for the

Niclausse boiler under special circumstances. Now, although it is true that these results were not always obtained under the best conditions for economical working, yet they throw light upon the possibilities of steam generation. They show, moreover, that we must aim at higher rates of evaporation than have been customary, and that in any deduction of the theoretically possible we must take into consideration such results, as well as those of C. R. Lang and of Professor Witz, for enlightenment as to the rate of heat transmission.

Weight and Space Occupied.—From the foregoing tables of results many figures can be gathered giving the weights of various boilers relatively to a standard of comparison such as the I.H.P. or the square foot of grate surface. It has been said that "the real coefficient of lightness, the weight per horse-power, is equal to the weight per square foot of grate surface divided by the maximum horse-power per square foot of grate surface, always supposing the weight of steam per horse-power required by the engines to be a constant quantity," but it is not apparent why the engines should be introduced into the elements of a comparison amongst boilers. It would surely be more direct and satisfactory to express the weight of the quantity of water evaporated from and at 212° F. per hour or per unit of surface by the boiler.

Some useful figures of comparison of the weights and space occupied by tubulous boilers in the French Navy were given by Mr. J. K. Robinson, and will be found reprinted in *Engineering*, Vol. lx., p. 750, etc. The following are two of the Tables given :—

TABLE CXIV.

DETAILED WEIGHTS OF BOILERS.

	D'Allest.	Belleville.	Niclausse.
Boilers proper	131·3	273·3	146·5
Uptakes	67·0		56·0
Accessories	11·8		6·6
Grates and fittings	19·1		18·3
Tools and spare parts	5·6	8·1	7·6
Feed pumps	5·2	11·4	5·2
Tanks	4·0	8·0	4·0
Smoke pipes	17·0	23·5	19·8
Floor plates and ladders	9·0	9·0	9·0
Fire-room ventilators	9·0	9·0	9·0
Air compressor	...	2·5	—
Separator	...	5·2	—
Water in boilers	53·0	16·0	53·0
Total of fire-rooms	332·0	365·0	335·0
Total of engines and boilers ...	757·0	801·0	760·0

In the case of the Niclausse Boilers—which were those of the Friant, the actual weight of the boiler as delivered was 329·0 tons, the boiler proper having weighed 202·61 tons and the uptakes only 10·76; the water in the boilers also was reduced to 46·18 tons.

The dimensions of the boilers are given in the following Table :—

TABLE CXV.

DIMENSIONS OF THE BOILERS.

	D'Allest.	Belleville.	Niclausse.
Number of fire-rooms	3	3	3
„ „ boilers	20	24	20
„ „ furnaces per boiler ...	1	1	1
Length of grate, ft. and ins. ...	6 ft. 8 in.	4 ft. 7 in.	6 ft. 8 in.
Width of grate, ft. and ins. ...	5 ft. 4½ in.	7 ft. 0 in.	6 ft. 0 in.
Total grate surface, sq. ft.	732	755·2	782·8
Total heating surface, sq. ft. ...	19,451	21,594	23,338
Ratio of H.S. to G.S.	26·6	28·6	29·8
Outside diameter of tubes, ins. ...	3·25	3·23	3·23
Inside diameter of tubes, ins. ...	2·91	2·86 & 2·60	2·97
Length of tubes, ft. and ins. ...	7 ft. 9 in.	6 ft. 4 in.	5 ft. 8½ in.
Diameter of circulating tubes, ins....	—	—	$1\frac{9}{16}$
Number of tubes in vertical row ...	10	9	9
Weight of water, tons	53	16·2	46·2
Volume of steam space, cubic ft. ...	1,879	784	830
Boiler pressure, lbs. per sq. in. ...	214	242	214
Pressure at engines	170	170	170

Comparison of the space occupied by modern forms of shell boilers of the Scotch and locomotive types with that required by tubulous boilers is afforded by the following two Tables taken from M. Bertin's work on "Marine Boilers." Fully detailed tables of weights will be found in that work at pages 218 and 355.

Table CXVI.

Boilers.		Name of Ship.	Horizontal projection in square feet. of the boiler c.	Horizontal projection in square feet. of the grate g.	Ratio $\frac{c}{g}$
Single-ended boilers.	2 furnaces	Sfax	102·39	42·95	2·384
			110·85	46·75	2·371
	2 furnaces	Manche	92·17	43·81	2·104
	3 furnaces	Amiral Baudin	106·3	63·61	1·671
	3 furnaces	Isly	150·16	73·74	2·036
			144·63	70·29	2·058
	3 frnaces.(old boilrs.)	s.s. Bretagne	145·12	70·07	2·071
Double-ended boilers.	3 furnaces (common combsn. chmbrs.)	Cécile	252·75	142·09	1·779
			250·0		1·759
	3 furnaces	Capitaine Prat	266·57	136·76	1·935
	4 furnaces (2 combustion chmbrs.)...	D'Entrecasteaux... ...	280·10	194·28	1·441
	4 furnaces (2 combustion chambrs.)	Columbia	329·33	168·01	1·960
Admiralty boilers.	3 furnaces	Hoche	216·62	70·00	3·094
	3 furnaces	Matsou-Sima	183·91	64·59	2·848
	2 furnaces	Dupuy de Lôme	201·48	57·15	3·525
	2 furnaces	Suchet	189·61	46·93	4·040
	2 and 3 furnaces ...	Linois	185·06	71·20	2·599
			161·52	51·99	3·107
Locomotive boilers.	1 furnace ...	Torpedo boats Nos. 105 to 114	94·81	24·76	3·830
	1 furnace ...	Torpedo boats Nos. 127 to 129	116·03	30·35	3·823
	1 furnace	Bombe	77·79	19·37	4·016
	1 furnace	Achéron	95·06	19·16	4·961

Table CXVII.

Type of Boiler.	Number of furnaces.	Name of vessel.	Horizontal projection in square feet. of the boiler c.	Horizontal projection in square feet. of the grate g.	Ratio $\frac{c}{g}$
Belleville	1 furnace	Alger	50·80	31·43	1·62
		Latouche-Tréville	70·07	43·38	1·61
		Bugeaud ...	54·89	34·44	1·59
		Bouvet	59·95	35·52	1·69
		Charlemagne / Gaulois ...	89·98	57·37	1·57
Oriolle	2 furnaces...	Zouave	54·25	31·43	1·73
	1 furnace ...	Torpedo boats 161-163 ...	41·97	24·22	1·73
D'Allest	2 furnaces	Bombe	107·10	50·59	2·12
		Jemmapes ...	138·52	80·73	1·72
		Chasseloup-Laubat ...	128·83	68·89	1·87
		Cassini	133·45	77·93	1·71
		Carnot	167·92	90·42	1·86
		Du Chayla ...	63·1	34·4	1·84
Niclausse	1 furnace	Friant	266·31	183·39	1·45
		Elan	44·56	21·42	2·08
Du Temple	1 furnace	Dragon	78·36	40·69	1·92
		Averne	75·75	38·21	1·98
		Torpedo boats 195-200 ...	112·48	45·21	2·49
Du Temple-Normand ...	1 furnace ...	Filibustier ...	90·42	33·37	2·71
Normand	1 furnace	Torpedo boats 148, 149 ...	121·07	35·74	3·39
		Torpedo boats 182-185 ...	116·23	38·75	3·00
		Forban	128·83	44·13	2·92
Normand-Sigaudy	2 furnaces	Château-Renault	239·7	96·4	2·48
		Dunois and Lahire ...	189·85	64·80	2·93
Guyot (Indre)	1 furnace ...	Jeanne d'Arc ...	101·7	46·16	2·19
Thornycroft	1 furnace	Véloce	99·14	37·99	2·61
		Coureur ...	112·38	38·10	2·95

Regarding these figures M. Bertin has remarked that the horizontal space required by a boiler may be expressed by the vertical projection of its horizontal dimensions to the grate area.

Thus the coefficient of floor space for the Niclausse Boiler comes out lowest at 1·5. The D'Allest Boiler 1·7 to 1·8, and the Belleville Boiler 1·6 to 1·7. The Du Temple coefficient averages 2·5 and the Normand 3. Double-ended cylindrical boilers have a mean coefficient of horizontal floor space at 1·75 and for single-ended boilers it reaches 2. Boilers of the navy type show from 2·6 to 4, and the locomotive pattern goes from 3·8 to nearly 5.

With these figures may be compared those given by Sir. A. J. Durston in Table CII. on page 561 *ante*.

The following gives the total weight per square foot of grate surface of various types of boilers :—

Cylindrical boilers, Admiralty type	1·124	tons
Single-ended cylindrical marine boilers ...	0·85	,,
Double-ended	0·814	,,
Locomotive marine boilers for ships ...	0·96	,,
Locomotive marine boilers for torpedo boats...	0·549	,,
Belleville Boiler	0·53	,,
D'Allest ,, ...	0·539	,,
Niclausse ,, ...	0·466	,,
Du Temple ,, (old type)...	0·329	,,
,, ,, (present)	0·411	,,
Normand ,, (present)	0·421	,,
Thornycroft ,, (old type)	0·356	,,
,, ,, ("Speedy" type)	0·453	,,

These are the weights for boilers of warships only. The weights of cylindrical boilers for two transatlantic liners amount to 1·27 tons per square foot of grate.

M. Bertin remarks :—

"The weight per square foot of grate surface of modern tubulous boilers considered suitable for use on large ships is very nearly half that of the ordinary return-tube cylindrical boilers. The weight of the lightest class of tubulous boilers is about one-third those of Admiralty cylindrical type, that is to say, nearly equal to the weight of water contained in these latter.

"The weight per square foot of grate would represent the relative weights of different boilers if the evaporative power per square foot of grate were the same for all. This is very far from being the case, especially in the Navy, where forced draught is almost universally used. The relative weights of

boilers can thus only be determined after very careful examination, which in the nature of the case must be incomplete, as it is impossible to determine with any exactness the maximum evaporative power of a boiler.

Weights of Water.—"The Admiralty type of cylindrical boiler contains 10·66 cubic feet of water per square foot of grate, and the return-tube or Scotch boiler 7·38 cubic feet, giving a mean of 9·02 cubic feet for cylindrical boilers. In locomotive boilers the mean is as low as 4·92 cubic feet, varying between 4·26 and 5·58."

Amongst tubulous boilers the Belleville has 0·855 cubic feet, the Niclausse 2·07, and the D'Allest type 2·69 cubic feet. Similar figures have been published from time to time for numerous water-tube boilers arranged for use on land, but those just quoted may be taken as typical examples of marine boilers.

Cost and Durability.—The only authentic figures of cost of water-tube boilers, as compared with cylindrical boilers, which have as yet been published, are those given by M. Bertin in his book. Writing in 1898, M. Bertin said :—

"The price per square foot of grate of the Belleville Boilers bought by the French Navy during the last few years, has varied between £27·12 and £35·62 ; on an average £31·96. The Niclausse boilers of the "Friant" have also cost £31·96. For the D'Allest boilers the price is a little higher ; it has ranged from £27·12 to £38·64 ; on an average £33·45.

"Comparing the average price of cylindrical boilers with the foregoing, we find it to be £32·7 for single or double-ended return-tube boilers, £48·31 for direct tube or Admiralty boilers, and £52·76 for boilers of the locomotive type. . . . In reckoning the performance per square foot of grate, tubulous boilers are 25 per cent. dearer than the return-tube boilers, but they are 10 per cent. cheaper than Admiralty boilers, which have in some cases supplanted the return-tube boilers.

"There is only one example of tubulous boilers of the second group being bought for ships other than small craft ; that is, the Normand boilers of the 'Dunois' and of the 'Lahire,' costing £64·65 per square foot of grate. This price hardly affords a fair comparison, as there is no analogous case in the other series of boilers excepting the cylindrical boilers of the 'Fleurus,' which cost £65·39. The Guyot boilers of the 'Jeanne d'Arc,' according to the highest estimate will only cost £44·59 ; this price is still high, but it falls below that of the Admiralty type boilers, and moreover it is unfair to the Normand and Guyot boilers to assume that the same amount of power per square foot of grate surface could be obtained from boilers of the Admiralty type as from them."

On the question of durability of water-tube boilers, there is more information available than is commonly supposed. An article in *Engineering* of the 27th December, 1867, from the pen of the late Mr. Ferdinand Kohn, and a letter in the same journal

of 23rd October, 1874, by the author of this work, contain the evidence that several examples of Rowan and Horton marine boilers continued in active service at a pressure of 120 lbs. per square inch for close on ten years, almost without repair, although subject to annual Board of Trade survey. At that time few cylindrical marine boilers were able to continue working at their original pressure of 50 to 60 lbs. for more than three years. In his paper on "Water-Tube or Coil Boilers," read at the Engineering Congress in Chicago in 1894, Mr. C. Ward mentioned that one of his boilers, having 700 sq. ft. of heating surface and 32 sq. ft. of grate area, had worked at 180 lbs. steam pressure for fourteen years, requiring the renewal of only two tubes during that time. Mr. Roberts also, in the discussion on that paper, stated that one of his boilers had been in use for thirteen years, during the summer seasons, and that it had received no repairs. Other makers had similar experience even then, and in fact the general result of American experience has been summed up by Professor R. H. Thurston in his contribution to the discussion on the author's paper "On Water-Tube Boilers" in 1897. "Durability," he said, "was a marked feature of this class of boilers with them (*i.e.*, the Americans), and the cost per horse-power hour or year was remarkably small, as reckoned on the repair and maintenance account. Their most extensive builders, after obtaining the statistics of between 100,000 and 200,000 h-p of their boilers in use, and from one to above twenty years' service, reported these costs, as an average, to fall under five cents per horse-power year. As to economy, they found records of trials in which an aggregate of above 3,000 tons of water was evaporated by 270 tons of fuel, an average efficiency which he thought the older types of boiler did not attain; it was within ten, perhaps seven, per cent of unity efficiency. During an experience in professional work of now 35 years, and dating from the earliest days of commercial use of this class of boiler, he had never known of their causing loss of life or of property by explosion. The comparatively few minor accidents recorded had been due to isolated cases of incomplete utilization of the fundamental principles of construction, or to exceptional mismanagement. If properly built and maintained in good order by regular and wise repair, they practically never wore out, and never endangered life or property. They bore hard driving,

and to an extraordinary amount; he thought their record was to-day vastly higher in this respect than any shell boilers. They enormously economised weight and space, and had always seemed to him certain, in time, to displace the older types, even at sea, where, indeed, they were particularly needed. Their latest experience with them lent additional confidence to their ultimate adaptation to even this trying duty, and if steam pressure continued to rise 50 per cent. per decade, it could not be long before they would entirely supplant the shell boiler in all naval and long voyage craft, and probably in all sea-going ships. The report of the Engineer-in-Chief of the United States Navy, just issued, dated October 1st, 1897, includes the following statement relative to the introduction of water-tube boilers into the batteries of boilers on naval vessels, a movement of supreme importance, and one which had, as already noted, been going on for a long time in that service :—'The gradual replacement on war vessels of the familiar cylindrical boiler by various forms of the water-tube boiler constitutes the most important fact in marine engineering at this time. For torpedo boats their superiority was so evident that they quickly displaced the older type and have been used exclusively for some years, although their first appearance (on the "Ariete") was only ten years ago. The particular form used in torpedo boats is, however, of such light scantling that hitherto there has been a fear that its longevity would not be sufficient to warrant the use of such boilers in large vessels. A different form has been in use in the French Navy since 1879, and has also been used in other navies, in some very extensively, but the saving of weight due to its use has not been so great as seems desirable if the cylindrical boiler is to be definitely abandoned. In 1888, this Bureau, alive to the supreme importance of light machinery for naval vessels, advised the Department to invite a competition of manufacturers of water-tube boilers with a view to the adoption of the successful one for use in a naval vessel. As a result of this action, coil boilers were installed in the "Monterey" in 1892, and have been in successful use ever since. This was the first instance of the use of light water-tube boilers for a large power (over 4,000 I.H.P.) on a large ship. It would have been easy for this Bureau to gain a cheap reputation for progressiveness by adopting this type of boiler at once for all ships, but there had not been suffi-

cient experience in the use of these boilers for extended cruising at sea to make such a step judicious, and for the highest efficiency of the fleet. The Monterey was expressly designed for coast defence, so that she would always be near repair shops if necessary, and her case was different from that of ships designed for general cruising. The conditions of the building of our new Navy made it imperative that every unit should be absolutely reliable. We were not adding to a navy up-to-date, but were replacing obsolete ships with modern ones. With only three battleships in commission, we could not experiment on the few additional ones authorised. Consequently, although realising the advantages of a reduction of boiler weights, if obtained without sacrificing reliability, the Bureau has used cylindrical boilers in the recent battleships. Meanwhile, experience of our own has been acquired from the service of the "Monterey," the "Cushing," and the "Ericsson," and careful attention has been paid to what is doing in the merchant marine and in foreign naval services. The last report of the Bureau showed the adoption of Babcock and Wilcox boilers for the "Chicago" and for the "Annapolis" and the "Marietta." Since then it has been decided, in the modernising of the "Atlanta's" machinery, to use this same make of boiler for about two-thirds of her power. The "Nashville" has Yarrow boilers for about the same fraction of power. As is shown elsewhere in this report, the "Annapolis," "Marietta," and "Nashville" have passed their contract trials successfully, and their water-tube boilers were entirely satisfactory. The Bureau feels that, with the experience now gained, the efficiency of the fleet will be best served by using water-tube boilers on future ships. As yet, it can certainly not be said that any one of the numerous varieties of water-tube boilers is absolutely the best. Some of the ablest engineers in the world have identified their names with particular forms of this type of boiler, and it is probable that, as experience accumulates, a form of boiler will be evolved embracing the best features of all of them.' "

In a paper on "Water-tube Boilers in the U. S. Navy," read in November, 1899, to the Society of Naval Architects and Marine Engineers in New York,[1] Admiral G. W. Melville, the Engineer-in-Chief of that Navy, said that the decision to adopt

[1] Abstract published in *The Mechanical Engineer*, December 16, 1899; see *Science Abstracts*, Vol. iii., p. 102.

water-tube boilers in all future vessels of their Navy was a natural step in the advance towards a perfect fighting machine. This opinion is all the more remarkable that in the same paper he announced that as an engineer he considers the design of these boilers to be wrong in principle, but he has become convinced that in spite of all drawbacks they are tactical necessities for warships. The grounds upon which he objects to their design are, that the pressure is borne on the inside, instead of on the outside, of the tubes, this being, he considers, the weakest part of the boilers; that there is a smaller quantity of water carried in these boilers than in the cylindrical type; that there is difficulty in observing the leaks in the tubes; and that the value of the heating surface is less than in the other design. There seems to be less force in the first objection than in the others, because in order to have a pressure of steam, some sort of vessel must be supposed, and the only question is as to the best form. The circular is the strongest form for resisting pressure, and the smaller the diameter the greater the strength per unit of surface. Tubes *as made* may be weaker under pressure from within than under conditions which expose them to a collapsing pressure, but that is a question of material and thickness, not of form. Moreover, in order to have any considerable amount of heating surface obtained from fire-tubes, a vessel of considerable size is required, as in the cylindrical boiler, with all its attendant drawbacks, in view of the higher pressure of steam. As to the other grounds of objection, the smaller quantity of water necessitates greater perfection in the feed arrangements, and more careful attention, which are by no means insuperable difficulties; and the heating surface question is in a fair way of being settled. "At first," says Admiral Melville, "the heating surface of water-tube boilers was made 3 sq. ft. per H.P., as against 2 sq. ft. necessary with cylindrical boilers. This figure has been gradually reduced, until now we are down to 2·4 sq. ft. of heating surface per H.P., about as low as I think it is yet safe to go with water-tube boilers. . . The ratio of heating to grate surface has been kept up to at least 40, although we do not yet feel warranted in allowing as small grate surface in water-tube as in cylindrical boilers. Water-tube boilers lose in efficiency when forced, especially those of the straight tube type. . . . The increased grate surface we have

acquired with water-tube boilers will be a positive advantage to our ships' steaming qualities. I consider that sustained sea speed depends largely upon the grate surface."

Since the "Cushing," all torpedo boats and destroyers in the American Navy have been equipped with water-tube boilers, which have proved to be quite as reliable as the light engines used in these vessels, and by making the attainment of higher speeds possible, have added to their efficiency and security.

The water-tube boilers in the "Monterey" (Ward boilers), the "Nashville" (Yarrow boilers), the "Marietta" (Babcock-Wilcox boilers), the "Annapolis" (Babcock-Wilcox boilers), and the "Chicago" (Babcock-Wilcox boilers), have come successfully through a considerable amount of service. The "Monterey" made a voyage of about 8,000 knots, largely under forced combustion, and, whenever possible, with all boilers in use. "There was no resultant injury to the water-tube boilers, which performed well throughout the trial, but the combustion chambers of the cylindrical boilers came out of the trial badly bulged." The "Marietta" made a trip around South America at the beginning of the war with Spain, and no repairs were required to the boilers after the completion of the trip. The "Annapolis" and "Chicago" also maintained the same level of excellence.

The boilers of the "Monterey" have been twice re-tubed on board the ship by the engineering staff there, without the necessity of laying up the ship at a Navy Yard, and in the case of the old monitors, "Canonicus," "Mahopac," and "Manhattan," the old rectangular boilers, which were worn out, were replaced by Babcock-Wilcox land-type boilers without disturbing the vessels' decks. The old boilers were cut up and passed out through the funnel, down which parts of the new boilers were passed. They were assembled in the engineroom space and erected in position, the whole operation having taken less time than was required for the construction of the original boilers.

In the case of vessels having protective decks, the facility with which water-tube boilers can be removed or completely renewed without disturbing the decks is of immense importance, and, with the result named above, is impossible with cylindrical boilers. The following vessels are being fitted wholly or partially with water-tube boilers :—The "Alert," "Atlanta," "Cincinnati," and "Wyoming," with Babcock-Wilcox boilers;

the "Maine" and "Connecticut," with Niclausse boilers; the "Missouri," "Wisconsin," and "Arkansas," with Thornycroft boilers; and the "Florida" with modified Normand boilers.

No trouble has as yet been experienced from salt water or grease in water-tube boilers, but in the short war with Spain several of the U.S. vessels suffered severely from dropped furnaces in their cylindrical boilers.

With regard to the accidents and failures reported against water-tube boilers, Admiral Melville says that we hear of all the failures, but the successes are not mentioned. He considers that the experience of the last ten years or more in the U.S. and other navies proves that water-tube boilers, when proper precautions are used, can be successfully adopted for the steam-generating plant of ocean-going vessels.

In the French Navy, according to M. Bertin, the Belleville boilers are the only type of tubulous boilers which have been in service for any length of time. "The ease with which the various elements can be replaced renders it very difficult to determine exactly the real life of the boiler; the replacing of the ash-pans and casings, which in itself is a small matter, is to some extent a guide in this direction. The Belleville boilers of the 'Milan' in 1891, had, in the course of a few months, several tubes pitted through sufficiently to put the boat out of service, although they were in good condition when she started, while on the 'Voltigeur,' the Belleville boilers, which have been renewed piecemeal during almost twenty years, have always behaved well, and successfully withstood the test of several long commissions.

"Just as unfavourable examples can be quoted for cylindrical boilers as for tubulous, as is evidenced in the case of the 'Marceau' during her Cronstadt commission, where the same thing happened as on board the 'Milan.' We may, therefore, arrive at the conclusion that the use of cylindrical boilers does not offer a guarantee of continuous satisfactory working much superior to that of the Belleville boilers. Further, exact comparison will never be possible between two durabilities of which one only can be defined. The cylindrical boilers of warships have a life of eight years, or at most ten, including at least one thorough overhauling during that period. They are then condemned and broken up, although still containing a good many

sound portions, because there is of necessity a limit to patching. At the end of ten years a tubulous boiler will not have experienced a thorough overhaul, but will have undergone a good many repairs; some parts may have been already changed twice, and even need replacing a third time, without in any way prejudicing those portions of the boiler which have remained intact; there is then no reason why the boiler should be condemned.

"The foregoing considerations appear favourable to tubulous boilers in regard to durability, but it would be unwise to generalise. Tubular boilers, in certain conditions of work and maintenance, have a very long life without necessitating any very extensive repairs." Instance the case of the White Star Company, where the boilers worked for twenty-four years, and that of the "Notre Dame du Salut," whose boilers had undergone twenty years of service up to the time when the vessel was chartered by the French Navy. "A tubulous boiler would not, in all probability, have reached this advanced age without having often had different parts replaced by new ones. . . . On the other hand, when the conditions are altogether against durability, as on torpedo boats, where locomotive boilers only last three years, tubulous boilers offer a decided advantage.

"Mr. Thornycroft states that his boilers usually stand eight years' service without extensive repairs, certainly without a thorough overhauling."

Although these remarks seem at present to put the case fairly, it must not be forgotten that a longer experience of tubulous boilers may materially change that aspect of this question. The proportion of tubulous to cylindrical boilers in actual use at sea is as yet small, and "it is unreasonable to suppose that, as experience accumulates, water-tube boilers will not be as durable as any others in proportion to the work done by them."[1]

Moreover, as Mr. Milton has remarked,[2] "it must be remembered that treatment is the most vital factor in the question, and that the present long service obtained from ordinary boilers has only been realised as the result of long years of experience

[1] "On Water-Tube Boilers," by F. J. Rowan. Trans. Inst. Eng. and Shipbuilders in Scotland Vol. xli., p. 35.

[2] "Water-tube Boilers for Marine Engines," by J. T. Milton. Min. Proc. Inst. C.E. Vol. cxxxvii., p. 301.

as to the best methods of management. There was a time when a life of eight years was looked upon as an excellent result, whereas now 20 years' service is by no means uncommon, and is often exceeded. If water-tube boilers become common, experience will doubtless soon show the best means of preserving them."

Hudson's Tables.—The following tables by Mr. J. G. Hudson, referred to in Chapter IV., show some of the results of trials already quoted herein, calculated out to show the disposal of the heat of the fuel and the velocity of the fire gases.

TABLE CXVIII.

Fire-box Evaporation, by formulæ (1), (2), *and* (3), *for various ratios of surface and air supply, assuming air at* 60 *deg., steam at* 340 *deg., and* 14,000 *units developed per* 1 *lb. of coal.*

F = H.S. per 1 lb. fuel.	A = air per 1 lb. fuel .. .. w = heat capacity of gases H_a = heat units available ..	12 lb. 3·12 13,126	18 lb. 4·56 12,723	24 lb. 6·0 12,320	30 lb. 7·44 11,917
sq. ft.					
·03	Absorbed per sq. ft.	44,533	29,600	21,910	17,100
	" " 1 lb.	1,336	888	657	513
	Temperature of the gases ..	4,119°	2,935°	2,284°	1,873°
·1	" " " ..	35,670	25,450	19,450	16,540
	" " " ..	3,567	2,545	1,945	1,654
	" " " ..	3,404°	2,572°	2,069°	1,733°
·3	" " " ..	23,163	18,177	14,783	12,327
	" " " ..	6,949	5,453	4,435	3,698
	" " " ..	2,320°	1,984°	1,654°	1,445°
·5	" " " ..	17,120	14,138	11,924	10,216
	" " " ..	8,560	7,069	5,962	5,108
	" " " ..	1,803°	1,580°	1,400°	1,255°
·7	" " " ..	13,579	11,566	9,990	8,706
	" " " ..	9,505	8,096	6,993	6,094
	" " " ..	1,500°	1,355°	1,228°	1,121°
1·0	" " " ..	10,363	9,088	8,035	7,150
	" " " ..	10,363	9,088	8,035	7,150
	" " " ..	1,225°	1,137°	1,054°	981°
1·5	" " " ..	7,430	6,697	6,059	5,500
	" " " ..	11,145	10,045	9,089	8,250
	" " " ..	975°	927°	878°	833°
2·0	" " " ..	5,791	5,301	4,863	4,469
	" " " ..	11,582	10,603	9,726	8,938
	" " " ..	835°	805°	772°	740°
3·0	" " " ..	4,0 8	3,742	3,486	3,251
	" " " ..	12,054	11,226	10,460	9,752
	" " " ..	683°	668°	650°	631°
4·0	" " " ..	3,079	2,891	2,717	2,554
	" " " ..	12,316	11,563	10,870	10,215
	" " " ..	600°	594°	582°	569°

TABLE

Source of data.		Per 1 lb. of coal fired.						Heat absorbed per sq. ft. of firebox.	Entering the tubes.			
		Heating surface.			Area through flues.	Air at 60 deg.	Heat developed.		Temp. of gases.	Speed per second.	Transmission.	
		Fire-box.	Tubes	Total.							Per deg.	Per sq. ft.
		sq. ft.	sq. ft.	sq. ft.	sq. ft.	lb.	units	units	Fah deg.	ft.	units	units
Report of the Research Committee, Inst. Mech. Eng.	Fusi Yama	·5	1·70	2·29	·0157	22·3	12,500	11,036	1285	17·63	4·2	4,120
	Colchester	·15	·86	1·01	·008	18·5	13,054	21,053	2165	42·2	8·82	16,237
	Tartar	·4	2·325	2·725	·022	31·6	14,700	11,200	1370	18·3	4·54	4,570
Mr. Spence's trials of a low Navy-type boiler.[1]	Natural draught ..	·28	1·34	1·62	·0109	16·6	13,000 ?	18,453	1916	25·2	6·3	10,162
	Cold forced do. ..	·24	1·08	1·32	·009	20·0	,,	17,216	1833	35·3	7·26	11,108
	Hot (261°) forced do.	·31	1·46	1·77	·012	18·0	,,	17,967	1879	24·3	6·12	9,645
Thornycroft's water tube boiler.[2]	D Natural draught	·4	8·6	9·0	·054	17·4	14,945	17,000	1885	5·25	2·92	4,395
	A ,, ,,	·24	5·26	5·5	·033	24·	12,600 ?	18,796	1608	10·45	3·76	4,610
	C ·27in. ,,	·143	3·137	3·23	·02	17·8?	14,500 ?	24,294	2500	18·8	6·5	13,812
	B ·49in. ,,	·09	1·96	2·05	·0123	13·14	14,270	26,089	2651	31·8	8·88	20,299
	E 2·00in. ,,	·046	1·004	1·05	·006	17·2	13,622	28,548	2878	66·4	13·6	33,973
Thornycroft's loco. type torpedo boiler.[3]	Draught 2in.	·06	·61	·67	·00313	20· ?	13,900 ?	24,683	2524	182·5	17·4	37,862
	,, 3in.	·05	·477	·527	·00246	18· ?	13,850 ?	26,760	2694	160·	20·	46,920
	,, 4in.	·04	·38	·42	·00197	16· ?	12,750 ?	29,275	2898	189·4	22·8	58,163
	,, 6in.	·031	·309	·34	·00160	14· ?	12,850 ?	33,097	3206	226·	26·9	76,907
R.A.S.E. portable engine trials at the Newcastle Show, 1887.	Alnwick	·4	1·105	1·505	·0084	23·2	13,264	12,820	1460	36·9	6·57	7,470
	Foden (simple) ..	·68	6·12	6·8	·03	12·42	13,964	13,628	1519	5·68	2·66	3,104
	,, (compound)	·56	5·09	5·65	·028	15·22	14,715	14,877	1697	8·16	3·46	4,460
	McLaren (s.)	·8	4·1	4·9	·0144	26·2	14,940	9,427	1194	20·8	4·51	3,832
	,, (c.)	·744	4·026	4·77	·014	27·48	14,880	9,458	1213	22·7	4·77	4,031
	D., P., and Co. (s.)	·83	4·58	5·41	·022	23·5	14,646	9,267	1164	12·	3·37	2,773
	,, (c.)..	·75	5·29	6·04	·0255	24·43	14,664	9,809	1247	11·4	3·42	3,013
	Humphreys (s.) ..	·32	1·56	1·88	·0116	17·4	14,738	19,187	2014	25·8	6·63	11,178
	,, (c.) ..	·237	1·203	1·44	·0089	23·57	14,076	16,846	1789	41·4	7·85	11,890
	Cooper	·35	1·62	1·97	·01	19·	14,544	17,014	1840	30·5	6·9	10,307
Mr. Stroudley.[4]	Gladstone	·092	1·108	1·2	·0028	18· ?	14,500 ?	26,717	2701	141·	18·9	44,290
	,, ...	·22	2·54	2·76	·0068	,,	,,	21,232	2215	49·1	9·8	18,191
Mr. Holliday[5]	Lancashire boiler ..	·3	3·46	3·76	·058	13·18	14,568	23,190	2299	4·36	2·94	5,880
Donkin & Kennedy[6]	Do. (same boiler) ..	·166	1·927	2·093	·032	17·00	14,539	24,801	2478	10·8	4·94	10,710
Mr. Longridge[7]	Lancashire boiler ..	·118	1·412	1·53	·0148	20·7	12,665	19,483	2053	24·4	6·53	11,271
	Do. (same)	·182	1·588	1·72	·0156	14·8	12,522	24,977	2488	18·4	6·4	13,853
Worthington pump trials[8]	Cornish boilers ..	·29	4·97	5·26	·084	16·42	14,800 ?	20,886	2142	3·53	2·53	4,642
University College	Loco. type ..	·37	2·09	2·46	·0204	27·2	13,900	13,160	1387	17·11	4·17	4,899
Donkin & Kennedy[9]	Do. (same) ..	·67	3·76	4·43	·037	40·7	14,816	7,537	1005	11·20	3·01	2,05[illegible]

[1] N.E.C. Inst. Engineers and Shipbuilders, 11th January, 1888. [2] Proc. Inst. C.E., v. 90. [3]
[7] Manchester Association of Engineers, January, 1890. [8] *Engineer*

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CXIX.

Leaving the tubes.				Temp. of the steam & water	Disposal of the heat developed by 1 lb. of the fuel.													
Speed per second.	Trans. per deg.	Temp. of the gases.			Apparent absorption by				Apparent total absorption.				Wasted in gases.				Actually utilised in raising steam.	
		Cal.	Act.		Firebox.		Tubes.		Calculated.		Actual.		Calculated.		Actual.			
ft.	un's	Fah deg.	Fah deg.	Fah deg.	units	%	units	%	units	%	units	%	units	%	units	%	units	%
10·87	2·43	615	578	304	5518	44·2	3810	30·5	9,337	74·7	9,547	76·4	3163	25·3	2958	23·6	8,570	68·6
20·96	3·83	845	835	324	3158	24·3	6218	47·6	9,376	71·9	9,427	72·2	3674	28·1	3627	27·8	8,240	63·
11·4	2·66	680	477	362	4480	30·4	5384	36·8	9,864	67·2	11,447	77·9	4830	32·8	3253	22·1	?	?
11·9	2·6	660	757	303	5167	39·7	6301	40·8	10,468	80·5	10,050	77·4	2532	19·5	2941	22·6	9,293	71 5
18·6	3·47	745	834	,,	4132	31·7	5416	41·7	9,548	73·4	9,099	70·0	3452	26·6	3901	30·0	8,981	69·1
11·7	2·58	660	701	,,	5570	42·8	5611	43·2	11,181	86·0	10,994	84·6	1819	14·0	2006	15·4	10,875	79·8
1·98	·97	424	421	380	6880	46·0	6456	43·2	13,336	89·2	13,330	89·2	1609	10·8	1615	10·8	12,944	86 7
4·78	1·56	485	474	382	3311	26·2	6739	53·6	10,050	79·8	10,116	80·3	2550	20·2	2484	19·7	?	?
6·15	1·82	535	540	375	3474	24·0	8884	61·2	12,358	85·2	12,334	85·1	2142	14·8	2166	14·9	12,056	83 0
10·91	2·5	605	610	365	2348	16·5	9415	65·9	11,768	82·4	11,740	82·3	2507	17·6	2530	17·7	10,964	76·8
22·2	3·84	735	777	380	1313	9·6	9359	68·6	10,672	78·2	10,489	77·0	2950	21·8	3133	23·0	9,940	72·9
56·6	6·28	815	1073	348	1481	10·7	8614	61·9	10,095	72·6	8,795	63·3	3805	27·4	5105	36·7	8,203	59·2
66·6	6·87	850	1192	,,	1338	10·0	8410	68 0	9,748	73·0	8,183	61·4	3602	27·0	5162	38·6	7,632	57·1
74·5	7·35	860	1260	347	1171	9·2	8315	65·2	9,486	74·4	7,854	61·6	3264	25·6	4896	38·4	7,341	57·5
81·0	7·64	855	1444	,,	1026	8·3	8462	68·5	9,488	76·8	7,368	59·7	2862	23·2	4982	40·3	6,910	55·9
22·4	3·69	705	700	328	5128	38·7	4389	33·1	9,517	71·8	9,546	72·0	3747	28·2	3718	28·0	8,791	66·2
2·42	1·03	382	388	350	9267	66·4	3661	26·2	12,928	92·6	12,908	92·4	1036	7·4	1056	7·6	12,319	88 8
3·46	1·33	455	435	407	8331	56·7	4844	32·8	13,175	89·5	13,253	90·1	1540	10·5	1462	9·9	11,843	80·4
11·3	2·3	435	441	353	7542	50·5	4950	33·1	12,492	83·6	12,452	83·3	2448	16·4	2488	16·7	11,853	79·3
12·4	2·45	448	460	368	7037	47·3	5197	34·9	12,234	82·2	12,152	81·7	2646	17·8	2723	18·3	12,162	81·7
6·63	1·75	432	385	341	8155	55·6	4303	29·5	12,458	85·1	12,735	87·0	2188	14·9	1911	13·0	10,819	73·9
6·0	1·7	440	410	366	7424	50·6	4922	33·6	12,346	84·2	12,529	85·5	2318	15·8	2135	14·5	12,545	85·5
11·3	2·6	625	480	328	6140	41·7	6101	41·4	12,241	83·1	12,882	87·4	2497	16·9	1856	12·6	9,795	66·8
21·9	3·7	730	700	338	3874	27·6	6249	44·8	10,123	71·9	10,300	73·2	3953	28·1	3776	26·8	?	?
14·2	2·8	615	680	358	5955	41·0	5925	40·7	11,880	81·7	11,568	79·6	2664	18·3	2976	20·4	10,384	71·4
44·	4·78	525	502	357	2458	17·0	9921	68·4	12,379	85·4	12,066	83·2	2121	14·6	2434	16·8	13,356	92·1
15·6	2·71	480	476	353	4671	32·2	8142	56·2	12,813	88·4	12,603	86·9	1687	11·6	1897	13·1	14,344	98·9
1·67	·94	600	309	208	6957	47.8	5775	39·6	12,732	87·4	13,416	92·1	1836	12·6	1152	7·9	9,621	66·1
4·61	1·73	790	690	304	4117	28·4	7268	50·0	11,385	78·4	12,077	83·1	3154	21·6	2462	16·9	9,679	66·5
11·9	2·8	770	700	327	2299	18·1	6667	52·7	8,966	70·8	9,331	73·7	3699	29·2	3334	26·3	8,339	65 7
7·2	2·1	690	648	326	3297	26·2	6881	54·7	10,128	80·9	10,288	82·2	2394	19·1	2234	17·8	9,472	75·6
1·4	·85	565	422	307	6057	40·9	6633	44·8	12,690	85·7	13,287	89·8	2110	14·3	1513	10·2	11,464	77·5
9·96	2·21	615	560	212	4869	35·0	5226	37·6	10,095	72·6	10,468	75·3	3805	27·4	3432	24·7	9,225	66 3
7·84	2·03	565	565	328	5050	35·3	4396	30·7	9,446	66·0	9,546	66·6	4870	34·0	4770	33·4	8,163	57·0

Ibid, v. 66. [4] Ibid, v. 81. [5] Ibid, v. 92. [6] *Engineering*, 1st August, 1890.
ing, 7th December, 1888. [9] *Engineering*, 21st November, 1890.

Table CXX.

"Alnwick" Portable, Detailed Calculation.

Particulars—

$H_d = 13,264$; $A = 23{\cdot}2$; $F = {\cdot}4$; $S = 1{\cdot}105$; $C = {\cdot}0084$; $T_s = 323°$

making:—

$$w = {\cdot}24 \times (23{\cdot}2 + 1.) = 5{\cdot}81$$

$$H_a = 13,264 - [5{\cdot}81 \times (323 - 60)] = 11,736$$

$$\therefore v = \frac{23{\cdot}2 \times (T_g + 461)}{144,000 \times {\cdot}0084} = {\cdot}0192\,(T_g + 461)$$

Fire-box:—

Units absorbed per 1 lb. $= 11,736 \times \left(1 - \frac{23{\cdot}2}{23{\cdot}2 + (45 \times {\cdot}4)}\right) = 5,128$

" " sq. ft. $= 5,128 \div 4$ . . . . $= 12,820$

Available units remaining in gases $= 11,736 - 5128$. $= 6,608$

Temperature of gases on leaving, $\frac{6608}{5{\cdot}81} + 323$ . . . $= 1,460°$

Tubes.	Intervals.					
	0 − ·05	·05 − ·15	·15 − ·3	·3 − ·5	·5 − ·8	·8 − 1·3
Surface in section, sq. ft.	·05	·1	·15	·2	·3	·5
Entering temperature ..	1460°	1396°	1280°	1136°	989°	827°
$v = {\cdot}0192\,(T_g + 461)$	36·88	35·65	33·42	30·66	27·84	24·73
Transmission per 1 deg., $\frac{T_g + T_s + 922}{2} \times \frac{\sqrt{v}}{1250}$	6·57	6·30	5·84	5·27	4·72	4·12
Degrees of diff. $= T_g - T_s$	1137	1073	957	813	666	504
Transmission per sq. ft. ..	7470	6760	5588	4284	3143	2076
" for section ..	373	676	838	857	943	1038
Fall of temperature	64	116	144	147	162	179
Final "	1396	1280	1136	989	827	648

Plotting the above temperatures, the ordinate corresponding with 1·105 sq. ft. gives 705 deg. as the final temperature, the speed at which is 22·33ft. per second, and the transmission per degree 3·69 units. The rates of transmission given as at entering and leaving tubes, are the rates calculated from the temperatures at these points, and therefore apply to succeeding sections, starting with these temperatures. The rates at the actual points of entering and leaving would therefore be somewhat in excess of those tabled.

A comparative view of these results is afforded by the following diagram :—

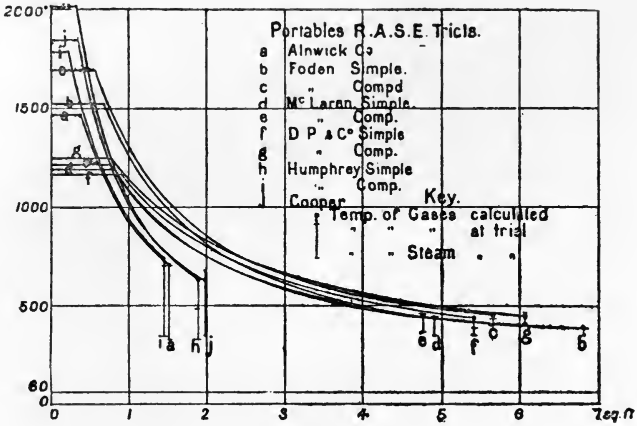

FIG. 314.

It is apparent from a review of results that none of the boilers hitherto introduced have attained a performance which entitles them to be considered as even approaching finality in their design.

Certainly none of them carries out to any degree of completeness the application of the principles discussed in this book, although there are evidences of attempts having been made in certain examples to reach a more thorough application of some of these principles. Attention has been directed to obtaining more perfect combustion in some forms of Babcock and Wilcox boilers, in the later Haythorn and Weir designs, and in those proposed for the American motor car as illustrated in the *Mechanical Engineer* of 9th April, 1898, and by Professor Watkinson in his patent, No. 13328 of 1898. The spiral movement of the heated currents of water has been provided for in Dr. De Laval's form of boiler, and this inventor seems also to have appreciated the importance of forced or accelerated circulation of the water. The boiler patented by Dagnell and Southey (see the *Mechanical Engineer*, 2nd April, 1898, page 360) also shows that an appreciation of the value of a spiral movement of the water is beginning to dawn upon

inventors, although in that special case that motion is utilised for other purposes than that of heat transmission. It is the better utilisation of the heating surface which offers the most promising direction in which improved evaporative results may be anticipated. Both water and gases should be caused where possible to travel over the surfaces with a spiral movement, and it is important that the two currents should move in opposite directions and at suitable velocities.

APPENDIX I.

THE modern history of forced draught appliances is fully described and illustrated in the following publications, which may be consulted for many details which are necessarily omitted from this work :—

Péclet, "Traité de la Chaleur," chaps. vi. and vii.

C. Wye Williams, "Fuel : Its Combustion and Economy," pp. 134-138.

F. J. Rowan, "The Design and Use of Boilers," *Engineering*, vol. xxvi., pp. 164-283.

F. J. Rowan, "Chimney Draught and Forced Combustion," Trans. Inst. Engineers & Shipbuilders in Scotland, vol. xxxii., p. 109.

Capt. Hamilton Geary, Journal Royal United Service Instn., vol. xxi. (1877), p. 956.

D. K. Clark, "The Steam Engine," etc., vol. iv., pp. 667-676.

" "Railway Machinery."

W. G. Spence, "On Forced Draught." Trans. N. E. Coast Inst. Engineers. Jan., 1888.

J. A. F. Aspinall, "The Draught of Locomotives." Inst. Mech. Engineers. 1893.

Engineering News, New York. June 7, 1890.

The Engineer, London. January 23 and February 6, 1891.

Transactions of the Inst. Naval Architects :

1880.	Papers by	J. F. Flannery.
1883.	"	R. ᵀ. Butler.
1884.	"	James Howden.
1885.	"	J. T. Milton and M. H. Robinson.
1886.	"	R. Sennet and James Howden.
1893.	"	J. D. Ellis.
1894.	"	F. Gross.
1895.	"	W. A. Martin.

A. J. Durston, Trans. Inst. Marine Engineers (1865) and Proc. Inst. C.E., Vol. cxix., p. 17.

James Howden, "Forced Combustion in Steam Boilers," Proc. International Engineering Congress, 1894, Vol. ii.

J. Patterson and M. Sandison, "Forced Draught," Trans. N. E. Coast. Eng., Vol. ii. (1886).

M. Paul, "Suction Draught," Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xl. (1897).

J. Thom, "Comparison of Systems," etc., Trans. Inst. Engineers and Shipbuilders in Scotland, Vol. xxxix. (1896).

J. C. Hoadley, "Warm Blast Steam Boiler Furnaces," Wiley and Sons, New York (2nd ed.).

APPENDIX II.

List of Writings on Heat Transmission.

1690. Sir Isaac Newton.
1818. Dulong and Petit, Ann. Ch. Phys. [2], vii., pp. 225-337.
1822. Joseph Fourier, "Théorie Analytique de la Chaleur" (Paris, 1822).
1835. Poisson, "Théorie Mathématique de la Chaleur" (Paris, 1835).
,, Despretz, Ann. Ch. Phys. [2], xix., 97 ; xxxvi., p. 422.
1840. E. Peclet, "Traité de la Chaleur" (3rd Edn., Liege, 1844).
1844. Wiedmann and Franz, Pogg. Ann., lxxxix., p. 497.
1848. T. Craddock, "Chemistry of the Steam Engine" (Birmingham, 1848).
1858. J. Graham, Proc. Lit. and Phil. Soc., Manchester, 1858, Feby.
1859. W. J. M. Rankine, "The Steam Engine and other Prime Movers."
1864. Colding, see Min. Proc. Inst. C.E., vol. lxxvii., p. 311.
1867. B. F. Isherwood, see "The Steam Engine," by D. K. Clark, vol. i., p. 14.
1871. J. Clerk Maxwell, "Theory of Heat" (London, 1871).
1875. Paul Havrez, Ann. du Genie Civil, 1874.
,, ,, ,, Etudes sur les Chaudières à Vapeur (Liege, 1875).
,, Gouillaud, Ann. Ch. Phys. [3], xlviii., p. 47.
,, Angstrom, Pogg. Ann., cxiv., p. 527.
,, Osborne Reynolds, Proc. Lit. and Phil. Soc., Manchester, vol. xiv. (1875).
1876. Heumann, Ann. de Ch. et Phys. [3], lxvi., p. 185.
1883. G. A. Hagemann, Min. Proc. Inst., C.E., vol. lxxvii., pp. 311-322.
,, A. Winkelmann, ,, ,, ,, p. 468.
1886. J. Fletcher, *Engineering*, vol. xlii., p. 69.
1889. C. R. Lang, Trans. Inst. Eng. and Shipbuilders in Scot., vol. xxxii., p. 287.
,, D. K. Clark, "The Steam Engine," etc., vol. i., pp. 13-81.
,, ,, ,, Manual of Rules, Tables, etc., p. 465.
1890. J. G. Hudson, *The Engineer*, vol. lxx., pp. 449, 483, 523.
,, ,, ,, ,, ,, ,, lxxvi., p. 107.
,, J. Hirsch, Bull. de la Soc. d'Enc. pour Indus. Nat., vol. v., p. 302.
1891. A. F. Yarrow, Trans. Inst. N.A., vol. xxxii., p. 98.
,, Louis Ser, Traité de Physique Industrielle, vol. i., pp. 225-227.
1892. A. C. Kirk, *Engineering*, vol. liv., pp. 78, 333.
1893. A. Blechynden, Trans. Inst. N.A. vol. xxxv., p. 70.
,, ,, ,, *Engineer*, lxxvi., pp. 98, 127 ; lxxxi., p. 509.
,, ,, ,, *Engineering*, lvi., p. 74 ; lx., p. 50.
,, A. J. Durston, Trans. Inst. N.A., vol. xxxiv., p. 130.
,, A. Witz, Compt. Rendus de l'Acad. des Sciences.
,, ,, Min. Proc. Inst. C.E., vol. cviii., p. 473.
1895. James Foster, "Evaporation by Multiple Effect" (2nd Edn., Sunderland, 1895).
,, A. Normand, Trans. Inst. N.A., vol. xxxvi.
,, C. E. Stromeyer, *Engineering*, vol. lviii., p. 443.
,, Lord Kelvin, Encycl. Brit., 9th Edn., Article Heat.
,, T. E. Stanton, Phil. Trans., A., 1897, vol. 190, pp. 67-88.
1898. J. Perry, Trans. Inst. E. and S. in Scot., vol. xlii., p. 63.
,, G. Halliday, Trans. Inst. E. and S. ,, ,, p. 41.
,, ,, ,, *Engineer*, vol. lxxxvii., p. 473, and 26th Dec., 1899, p. 653.
,, E. M. Bryant, Min. Proc. Inst. C.E., vol. cxxxii., p. 274.
1901. E. C. Schmidt, *Railroad Gazette* (New York), vol. xxxiii., pp. 408, 409

APPENDIX III.

ON BOILER INCRUSTATION AND CORROSION.

THERE is perhaps no subject connected with Engineering Science which at the present time commands more attention or causes more perplexity than does the compound subject of this paper. In Marine Engine practice its difficulties are most keenly felt ; and of itself that is a field of operation large enough, as it involves interests sufficiently extensive to give great importance to the subject, and to demand the utmost exertions of engineers towards the solution of its problems, and the providing of remedies or preventive measures against the ravages of what is an active and powerful agent in the destruction of their works. But the range of action which this destructive agent has is bounded only by that which puts a limit to the use of steam, and hence many other interests besides those of engineers are involved in the matter.

The state of general information about this subject is very unsatisfactory, because it amounts only to the fact that obscurity, or at least uncertainty, prevails. Yet many facts of the greatest interest and importance have been observed and noted, and, as is usual in such cases, there are some men who have considered these in the light of their own experience with the intelligence which is needed in order to turn all to good account. As the subject is partly a chemical and partly a mechanical one, it demands, in order that it may be successfully grappled with, a combination of scientific and practical information which, in consequence of defective educational methods, has not frequently been found among engineers.

I propose to myself in this paper the simple task of bringing together these scattered facts and observations, adding to them in whatever measure I am able, in order to elucidate if possible the full truth of the matter. The course of investigation and inquiry which have been called forth has been marked by the suggestion of various remedies. The earlier stages have produced the recommendation of a variety of empyrical remedies or nostrums—substances which have been proposed apparently for every conceivable reason except an intelligent perception of the nature of the action to be counteracted, and consequently of the qualities requisite in the remedy. A list of these applying to Incrustation is given in a paper by Mr. James Napier, published in the *Proc. of the Phil. Soc. of Glasgow* (vol. iv., 1855–58), who gives also some account of the more rational methods proposed in his day. For Corrosion a similar list has in recent times appeared—too large, however, to quote at length ; and some methods of working have been proposed which have been more or less successful under special circumstances, but all partial in their application. Of these are the endeavour to form a scale of salt by the use of a proportion of sea water, the use of zinc in the boilers, filtering the feed water, etc.

There seems to be in some quarters the idea that Incrustation and Corrosion of Boilers, inasmuch as in general they both result in the destruction of the boilers, are one and the same action. But although this is an error, and the two actions are very dissimilar, yet they are so often united in effecting the destruction of boilers (and almost all crusts contain iron), and are so often present successively in the same boiler (*i.e.*, a crust being formed and then decomposed or partially decomposed, with injury to the boiler), that an

examination which did not include a notice of both could not lay claim to any degree of completeness.

INCRUSTATION.

A few years ago the attention of all concerned was exclusively directed to Incrustation, its evils and prevention. The evils produced by it are numerous, for boilers, when coated with crust, quickly accumulate layers of this material, which is a bad conductor of heat, and thus are not only hard to steam, requiring a large excess of coal, but are more quickly worn out and sometimes suddenly oxidised or "burned," in consequence of the increased temperature rendered necessary in the furnaces. Dr. J. G. Rogers, of Madison, U.S., in a paper published some years ago, estimated the conducting power of crusts as compared with that of iron as 1 is to 37·5. A scale $\frac{1}{16}$ inch thick, he says, requires an extra expenditure of 15 per cent. more fuel, and this ratio increases as the scale is thicker. Thus when it is $\frac{1}{4}$ inch, 60 per cent. more fuel is needed; $\frac{1}{2}$ inch, 150 per cent., etc. The temperature of the heating surface of the boiler must be raised in proportion to the thickness of scale. Thus, while to produce steam of a pressure of 90 lbs., water must be heated to about 320° Fahr., and this can be done in clean boilers with $\frac{1}{4}$-inch plates by heating the boiler surface to about 325°, if $\frac{1}{2}$ inch of scale intervenes between the shell and the water, it will be necessary to raise the temperature of the heating surface to about 700°—almost low red heat. Iron oxidises the more rapidly the higher the temperature at which it is kept, and at any heat above 600° it very soon becomes granular and brittle, and is liable to give way under pressure. This condition predisposes the boiler to explosion, and makes expensive repairs necessary, and the presence of scale also renders the raising and lowering of steam slower. (*Chem. News*, vol. xxvi., p. 17.) The proper circulation of the water is also interfered with by the presence of crust. Both economy and durability thus require the absence or prevention of crust.

There are two distinct classes of boilers which are subject to incrustation, and these are—

1. Land boilers using natural fresh waters, and
2. Marine boilers using sea water.

1. There is no doubt that the quality of natural fresh waters varies between wide limits, from rain water on the one hand, which contains no mineral impurities, to that of highly charged mineral and chalybeate springs on the other. But in this matter, as in every other, extreme or exceptional cases always demand exceptional treatment, and, therefore, we shall leave these aside and consider the more general and useful aspect of the subject.

An examination of the analyses of waters supplied to the principal manufacturing towns in Britain (such as, for instance, are published in the Report of the Registrar-General, Vol. VI.) and comparison with that of rivers in other countries, demonstrates that no better general or average illustration of this class can be met with than is afforded by the River Clyde water, which was in general use in this city and neighbourhood prior to the introduction of Loch Katrine water, and which is still used in some manufacturing establishments. As analysed by Dr. Wallace in 1848, that water contained the following impurities, which are here tabulated in grains to the gallon :—

Clyde Water as Supplied to Glasgow in 1848.

Carbonate of lime...	2·52
Carbonate of magnesia ...	·72
Sulphate of lime ...	·26
Sulphates of potash and soda ...	1·94
Chloride of magnesium ...	·40

Chloride of sodium	·54
Oxide of iron	trace.
Phosphate of lime and alumina	·31
Silica	·28
Organic matter	·89
Total	7·86

Dr. Wallace (to whose courtesy I am indebted for the above and other information on this subject, and for much valuable assistance in connection with this paper) has informed me that the total amount of solid matter in solution in this water increased in quantity gradually, and that in 1854 it amounted to 10 or 11 grains per gallon.

The incrustation formed upon ordinary steam boilers working in mills at from 15 to 20 lbs. per square inch pressure of steam (above the atmosphere) and using that water, analysed by the same authority, is found to consist of :—

	Per cent.
Carbonate of lime	66·00
Magnesia	6·05
Sulphate of lime	4·28
Water, with traces of carbonic acid	8·72
Oxide of iron, alumina, and phosphate of lime	5·85
Silica	8·10
Organic matter	1·00
	100·00

This crust, which is of a dark brown colour, and is hard, forms rapidly on the interior of the boilers, and is difficult to remove. But it has been found that by a moderate use of soda ash, this formation is readily stopped or held in check.

The quantity of soda ash used in a pair of boilers—one 30 horse-power, 6 ft. 6 diam. × 21 ft. long ; one 40 horse-power, 7 ft. 6 diam. × 27 ft. long—which together require about 9700 gallons of water per week, is 6 lbs. per week in both boilers. This is dissolved in water, and fed into the two boilers once a week.

The action of this soda ash or carbonate of soda, under these circumstances, is a very interesting one, though perhaps not well understood by those using the substance in this way. Sulphate of lime is decomposed by its means and precipitated as carbonate, while a soluble sulphate of soda is formed. The neutral carbonate of lime is likewise produced by reaction from the bicarbonate in solution, and, as thus formed, it will not adhere to the boiler surfaces, but separates as a loose powder or mud, which can be blown out of the boilers or otherwise removed as sludge. In those boilers under notice the quantity of this sludge is found to be three pails full from each boiler every three months.

It has been found, however, that where the neutral carbonate of lime is produced slowly by the action of heat—which drives off part of the carbonic acid from the bicarbonate existing either in solution in the water or as a solid already deposited upon the boiler surfaces—that in this case the neutral carbonate possesses the property of being able to adhere firmly of itself to the boiler plates. It seems to be in this case partially crystalline. Thus, the special advantage arising from the employment of soda ash is that it decomposes the bicarbonate rapidly, probably because of the presence of some soda uncombined in the ash, and that the neutral carbonate is precipitated as a loose powder, which will not adhere unless fused or agglomerated by means of some other substance.

Concerning this latter point, M. Bidard, of Rouen (a French chemist who has written largely on this subject in the *Annales Industrielles*, and in a Belgian journal entitled the *Moniteur de la Brasserie*), has informed me that his numerous examinations of boiler incrustations have demonstrated the fact that the presence of organic matter is necessary for the formation of boiler crusts, which consist essentially of carbonate of lime. Such crusts he has produced artificially, in order to verify his theory.

He says in one letter, " Lorsque le carbonate de chaux neutre se dépose au sein de l'eau que le tenait en dissolution s'il rencontre de la matière organique en dissolution, bois, extrait de teinture, savon de resine, jucus, &c., &c., il s'y combine et forme avec elle une combinaison insoluble. Elle se dépose sur les parois de la tôle (toujours plus chauds que l'eau), elle s'agglomère à une pression de 6 atmospheres, par exemple, ou 160° de chaleur, forme une pâté qui *cuit* comme de la pâté à farine et produit l'incrustation. J'ai en ma possession des incrustations qui contiennent 16 pour cent. de matières organiques."

Fresenius, however, quoted by Dr. Wallace (*Proc. Phil. Soc., Glasgow*, vol. iv., p. 319), without specially noticing the presence of organic matter, has attributed a cementing property to sulphate of lime, which he always found present in boiler crusts.

M. Bidard's explanation thus applies specifically to those crusts which contain carbonate of lime and no sulphate, for it is probable that where sulphate is present it possesses agglomerating power of itself sufficient to render the presence of organic matter unimportant in these instances. This is demonstrated in examples, in some marine boilers for instance, where crusts are formed without organic matter being present in appreciable quantity, of which the analyses, on page 609, by Dr. Wallace are specimens. But M. Bidard's remarks show that soda ash might be used with muddy water, such as canal water for instance, and yet a hard incrustation would form. In such a case there would be no preventive but the use of a filter for all the water passing into the boiler in addition to the use of soda ash there.

The use of too much soda ash is injurious in its effects, as the excess boils up and passes over in the steam to cylinders and pumps, where it clogs the pistons, and otherwise interferes with proper working by making combinations with the oils and greasy matters employed in the machinery. The lavish use of oils and grease, of course, intensifies this action where it is present, and it has been found that the carbonate of lime itself has passed over from the boiler with the steam and has entered into combination with the grease where enough was to be found. " La decomposition de corps gras dont vous me parlez," writes M. Bidard, " ne va pas jusqu'au charbon seulement, il se produit là une combinaison de corps gras et de chaux provenant de carbonate de chaux, autrement dit savon de chaux, très prejudiciale pour la tôle des chaudières. J'ai été dernièrement temoin et expert d'un fait très curieux. Le carbonate de chaux entrainé par la vapeur est arrivé dans le corps de pompe—il a formé avec la graisse un savon de chaux tellement abondant et dur que la piston s'est subitement arrêté."

All that is needed, however, in working with soda ash is a little intelligent care, and, as the matter is simple, a system of working is soon arrived at. As an example, I take the boilers already mentioned at Barrowfield. Under ordinary circumstances the manager proceeds, as I have said, blowing out the boilers once in three months. When, however, there is a fresh or " spate " in the river the quantity of inorganic solids in the water is proportionately less, and the quantity of soda ash introduced is in consequence diminished. Muddiness in the water, seen in the gauge glasses is a sure test if too much is being used, and when this is noticed and

acted upon no inconvenience from material passing over to the cylinders is found to result.

An interesting fact may be mentioned in connection with this part of the subject and as illustrating how calcareous waters sometimes contain soluble matters which themselves counteract their crust-forming ingredients. The boilers of an engineering works in M'Neill Street use the water drawn from the Clyde at a point which is considerably below Barrowfield, the water being contaminated by the refuse from print works and other factories discharged into it between the two points.

A comparative estimation, by Dr. Wallace, of the qualities of the water from both localities is here tabulated :—

	I. From Barrowfield.	II. From M'Neill St.
Total solids per gallon	8·96	15·12
Insoluble in water, carbonates of lime and magnesia, silica, etc.	2·94	3·78
Soluble salts	3·92	6·72
Organic matter, etc. (loss by ignition)	2·10	4·62
Alkalinity expressed in soda	·014	·056

The marked difference in amount of total solids per gallon, and in the amount of soluble salts and degree of alkalinity, shows that a decided change has been effected in the water by the time it reaches M'Neill Street. In using it in the boilers there, it is only after a considerable time, and in corners of the boiler, that a crust is formed. The ingredients of the water seem in general to react naturally, and in regular working only a deposit of loose mud collects, which is blown out of the boilers each morning.

The composition of the crust, as analysed by Dr. Wallace, is given below, but a full analysis of the water would be required in order to show what re-actions took place in working :—

Carbonate of lime	64·98
Sulphate of lime	9·33
Magnesia	6·93
Combined water	3·15
Chloride of sodium	·23
Oxide of iron	1·36
Phosphate of lime and alumina	3·72
Silica	6·60
Organic matter	1·60
Moisture at 212° F.	2·10
	100·00

The use of soda ash as a preventive of the formation of incrustations in boilers working with calcareous waters is so rational and simple that it has, from a comparatively early date, commended itself to chemists, and has been by them repeatedly proposed to engineers. The material itself possesses for the majority of cases, where such is called for, all that it is requisite an anti-incrustator should possess, while, if used with average care and intelligence, it is not capable of acting destructively. Its application is simple, as it may be added in solution either periodically—as in the case of the boilers quoted—or, better, regularly and steadily in fixed proportion to the quantity of water fed into the boiler, after the manner proposed by Mr. James Napier in the paper already alluded to. There is also no reason why it should not be added in proper proportion to the water in the feed tank or cistern, instead of being put into the boiler. In this way, as the re-action between soda ash and sulphate of lime does not require a high temperature or pressure, the precipitated carbonate of lime could be

arrested, and comparatively pure water fed into the boilers, frequent blowing-off being also rendered unnecessary.

With waters containing only a little sulphate, and chiefly carbonate of lime, it would be necessary, however, to introduce the soda salt into the boiler, as a temperature of 100° Cent. (212° Fah.) is requisite for the decomposition of the bicarbonate of lime.

A short examination of the various remedies against incrustation which have been proposed will not be uninteresting, although it results in the conviction that most of them are unsatisfactory.

Oxalate of soda and tannate of soda were proposed by Dr. Rogers in America, in order to form, by decomposition of the lime salts, insoluble oxalates and tannates; but these would seem to increase the amount of solid matter precipitated, and, although proposed some years ago, to have been little used.

Lime and zinc have been used with some degree of success, but their action is confined to combining with the carbonic acid of the bicarbonate of lime. On sulphate of lime they have no action.

The object in view in the proposed use of starchy and gelatinous matters has been to prevent scale forming, by enveloping the precipitated or crystallised solids with gelatinous covering, and so to delay their settling by diminishing their weight. But M. Bidard's observations on the effects of the presence of organic matters (especially in so-called "anti-incrustators," or compounds for preventing incrustation) at once sweep the field of all remedies of an organic composition, proving them to be injurious by doing the very thing which they are supposed to prevent.

Referring to this point, he says, "Je connais à Rouen une chaudière de la force de 30 cheveaux qu depuis 1852, n'a subi aucune reparation aucune avarie. Elle marche cependant alimentée par de l'eau calcaire, le netoyage ne donne que de la boue, jamais de calcin adhèrent—*il n'entre dans la chaudière aucune substance organique.*"

Still, however useful as a precaution where the admission of extraneous organic matter can be prevented, this, as a system of preventing incrustations, manifestly fails where the water contains organic matter in solution.

Sal-ammonia, proposed by Ritterbrandt, and hydrochloric acid, are both open to the objections that their preventive action is only partial, and that they have the power of seriously injuring the boilers and connections.

Crude pyroligneous acid has been suggested for action upon carbonates alone, while petroleum has been extensively used in the United States with a measure of success, not only in preventing incrustations, but also in removing those already formed. Its action has not as yet been investigated, as far as I am aware, but it is probable that its effects are due to decomposition of hydrocarbons. This seems to be borne out by a report by the Chief Engineer to the Steam Boiler and Inspection Coy. of Hartford, U.S. (an extract from which appeared in the *Engineer*), who states that "petroleum works better where sulphate of lime predominates than in waters impregnated with carbonate of lime. We would not," he says, "advise it in connection with this latter." This simple fact renders it useless in the majority of boilers using fresh water in this country.

Soap acts upon both carbonate and sulphate of lime, but the quantity appears to be increased by the formation of lime soap, and thus the boiler is made filthy; a corrosive crust is sometimes formed, and priming and other evils also result from its use.

Recently a substance called "Burfitt's Composition" has been patented for the prevention of boiler incrustation, but it has been found to consist essentially of organic matters, and, moreover, has rather increased than prevented incrustation where it has been used. (See *Jour. Chem. Soc.*, Jan., 1876, p. 134.)

Two other methods of prevention have also been devised, and seem to be founded upon the fact which Professor Mills informs me was first observed

by J. Y. Buchanan (*Proc. Royal Soc. of London*, 1873-74, vol. xxii., pp. 192 and 483), that barium chloride decomposes sulphates and liberates the carbonic ac d in water.

One of these, called "De-Haën's Process," which consists in the use of barium chloride and milk of lime, is now extensively used in Austria and in Krupp's Works in Prussia. A recently published statement of the comparative cost of working on this system, and with water containing gypsum, without an added reagent, shows that to purify 33 cubic metres of water when containing 5 parts gypsum in 100,000, the cost is 6d., and when containing 30 parts gypsum the cost is 3s. Practical working with this process for 12 months with one or two boilers (it does not appear very clearly whether one or two) showed an increase of expenditure amounting to 500 florins, against which was to be placed the saving in fuel resulting from absence of incrustation, and reduced repairs from the same cause, the value of these however not being stated. (*Dingler Polyt. Jour.*, ccxvii., 338 ; *Chem. Soc. Jour.*, No. clxi., p. 799.)

The analyses (given March, 1876, *Chem. Soc. J.*, No., clix., p. 450) of deposits which have been found to accumulate in the steam pipes, etc., where these processes have been used, impress us with the idea that these methods are, however, open to some serious objections in practical working on account of the formation of salts of barium.

There is, however, one system of working which has yet to stand its trial, but which it is perhaps not extravagant to consider as inseparably connected with the advancement of engineering science and appliances upon which alone it depends. That is the working of land boilers in connection with surface condensers, and so supplying them with pure water. No incrustation is possible with this method, and its theoretical advantages in point of economy seem to justify the belief that its present limited adoption will prove merely the precursor to its more general introduction. It becomes of all the more importance in view of the extended use of sectional or water-tube boilers, because with these, on account of small water spaces, no mere preventive measures against the formation of incrustation suffice. Solid matters ought to be excluded from all such boilers.

2. It is necessary, in connection with incrustation, to consider marine boilers working with sea-water, because although modern systems of marine engine practice with compound engines and surface condensers, wherever these have been adopted, have banished incrustations ; yet these systems have not yet been universally adopted, and there is even a disposition with some to return to the régime under which incrustation held sway. The evil effects of incrustation make themselves felt with multiplied force in marine boilers, because of the great rapidity with which the crusts form, in consequence of the large quantity of solids contained in the water. I am informed by Mr. Tookey, of the Royal School of Mines, that British Channel water contains 2467 grains, and North Sea water 2408 grains in the gallon ; and it has been shown by Mr. James R. Napier, F.R.S. (*Proc. Phil. Soc. Glasgow*, vol. iv., p. 281), that sulphate of lime begins to deposit before one half of the water is evaporated.

In addition to this rapidity of formation of crust, the space at command for storage of fuel is limited. Large quantities of chemical reagents cannot for a similar reason be carried ; and because of the confined space in which boilers and men working at them are placed on board ship, the results of an accident to, or the destruction of, the boilers are serious ; while great difficulty is also experienced in getting repairs effected in foreign ports generally. All these considerations render it of the greatest importance that marine boilers should be freed from incrustation. Besides these, there are reasons connected with the formation of sea-water scale which render its presence in boilers undesirable.

Considered from a chemical point of view, the problem of preventing incrustation in these boilers appears to be similar to that experienced with land boilers, inasmuch as the substances composing the crusts are similar in both cases, although differing in their proportions in the formations. No doubt, as we have seen, soda ash is the best chemical preventive, where that substance has to be used in ordinary circumstances, but the comparatively enormous quantity of solid matters present in sea-water causes the use of soda ash to be attended with so many inconveniences, and so much expense, as to render it here practically useless. In these circumstances it has to be combined with blowing off from the boiler in order to get rid of the solids, it being necessary, as Mr. J. R. Napier showed, to blow off $\frac{1}{10}$ of the feed water, and neutralise the sulphate of lime in $\frac{8}{10}$ with soda. The loss of heat from this blowing off is considerable, and it is combined with the cost of the large quantity of soda required for neutralising. Yet this process is not worse than the ordinary mechanical one of discharging the saturated, or what is supposed to be the saturated, water from the boilers which has been most generally resorted to. In this case the indications of the salinometer are depended upon, and fully $\frac{5}{10}$ of the feed water have to be discharged. little of its heat being utilised. With regard to this Mr. Jas. R. Napier has said of the example of a vessel whose boilers worked at a temperature of 270° that "a quantity of fuel equal to 15½ per cent. of that which produces evaporation is consumed by the ordinary blowing-off method in order to prevent crust, and this amount increases with the temperature."

The salinometer might prove, and perhaps has often proved, a fallacious test, for if it were applied after a large quantity of the solids had been precipitated from the water, it would deceive the engineer by showing a less density than had existed previously, and thus mislead him as to the state of the boilers and of the water. In result it has been always necessary to chip and hammer away scale from the interior of marine boilers worked with sea-water to an extent not advantageous to them.

Undoubtedly the most sensible and efficacious method of preventing incrustation in these boilers is to work with fresh water. This has been rendered possible in many instances by the introduction of the Surface Condenser into practical working, and no doubt the desire to avoid the evils of Incrustation has operated in bringing about the introduction of that system which is at present the most general in marine engineering. On the other hand, however, the commencement of this era in engineering practice has been the introduction of engineers to all the evils and difficulties of Corrosion.

Before dismissing the subject of Incrustation, I wish to direct attention to the following analyses and notices of the decompositions which take place in sea water in boilers during the formation of crusts, as these throw considerable light on the subject of Corrosion. The following analysis of Black Sea water was given me by the late Professor Penny. I quote it only as showing the various ingredients contained in sea-water, as I have no means of ascertaining its accuracy now—

Black Sea water, sp. gra.	1·01365
Chloride of Sodium	14·020
" Potassium	·190
" Magnesium	1·310
Bromide of Magnesium	·005
Sulphate of Lime	·105
" Magnesia	1·470
Carbonate of Lime	·365
" Magnesia	·209
Total salts in parts per 1000	17·674

The following analyses were made by Dr. Wallace: Nos. 1, 2, 4 and 5, for a paper of his on Boiler Incrustation (*Proc. Phil. Soc. Glasgow*, vol. iv., p. 317) published some years ago; the others were kindly undertaken for me along with other investigations inserted in this paper.

No. 6 differs from the rest in being merely a deposit. I have arranged them in tabular form, in order to show as far as possible their relation to one another as having been formed at different pressures of steam—

Analyses of Boiler Crusts and Deposits.

	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.
Sulphate of Lime	33·95	66·88	69·77	74·21	72·85	57·34	76·83
Magnesia	40·05	18·96	15·75	14·95	13·18	1·94	1·81
Carbonate of Lime	—	—	3·44	—	·34	—	—
Common Salt	traces.	traces.	·99	2·04	2·16	1·72	2·24
Phosphate of Lime, Alumina	1·33	·50	1·14	1·34	2·40	—	—
and Oxide of Iron ...	—	—	·22	—	—	27·04	13·76
Silica	traces.	traces.	·16	·57	·80	7·60	2·24
Water with traces of Carbonic Acid	24·67	11·66	8·25	6·89	8·27	4·30	3·78
	100·00	100·00	99·72	100·00	100·00	99·94	100·66

No. 1 is from the Cunard steamer Asia, probably worked at about 4 or 5 lbs. per square inch pressure of steam.
No. 2 is from the King Orry, worked at about 5 to 10 lbs. pressure.
No. 3 " Propontis, " " 10 " " Old boilers.
No. 4 " Cosmopolitan, " " 10 to 15 " "
No. 5 " Source unknown " " (?) 15 to 20 " "
No. 6 " Propontis, " " 150 " " Deposit before sea-water was fed into Boilers.
No. 7 is from the Propontis, worked at about 150 lbs. pressure, Crust after sea-water was fed into Boilers.

Dr. Wallace, in his paper quoted above, remarks, "These crusts differ from the insoluble matter obtained by simply evaporating sea-water in open vessels, for that contains nearly four times as much carbonate of lime as carbonate of magnesia, while the crusts contain a large quantity of magnesia, and little or no carbonate of lime. The decomposition of soluble magnesian salts by carbonate of lime under the influence of a liquid boiling at a high temperature (say 270°) is exceedingly interesting. Sulphate of magnesia and carbonate of lime boiled with water under ordinary circumstances do not re-act upon each other in the slightest degree; but it is evident that the result is brought about under pressure. The re-action with oxide of manganese, which is isomorphous with magnesia, is exactly similar, and is taken advantage of in the recovery of the manganese used in the preparation of chlorine, as practised at the St. Rollox Chemical Works.

"Again, the condition in which the magnesia occurs is peculiar. We should expect a basic carbonate, but I find little more than a trace of carbonic acid in any of the crusts. (In No. 1 it was ·28). The magnesia exists essentially as the hydrate. The sulphate of lime appears to occur as the hydrate described by the late Professor Johnson, as having been found by him in a distinctly crystallised condition in a high-pressure steam boiler, its composition being represented by the formula $2(CaOSO_3)+HO$." This fact is stated by Gmelin, *Handbook of Chem.*, Vol. iii., p. 201.[1]

[1] Under the head Di-hydrated Sulphate of Lime, Gmelin says:—This compound was deposited from the water in a boiler which was working under a pressure of two atmospheres; it formed a greyish granular mass of specific gravity 2·757, appearing under the microscope in the form of

Recently these results have been verified by the independent investigations of Dr. Ferd. Fischer (published in *Dingl. Polyt J.*, ccxii. 208-220, and noticed in *Chem. Soc. Jour.*, Oct., 1874, vol. xii., p. 1021), who has proved from a number of analyses that various decompositions of the salts contained in waters take place under the influence of elevated temperature and pressure. Fischer quotes various authorities to show that gypsum gives off nearly half its water of crystallization at temperatures up to 100° (C.), and further proportions at higher temperatures, so that its solubility is considerably diminished. Above 140° it becomes totally insoluble in sea-water, and at a lower temperature in fresh water, and hence is deposited as an anhydride. It is more easily soluble in water containing sodium or magnesium chloride in solution than in pure water. The effect of pressure on its solubility and that of other salts is shown by the following table of analyses of water from boilers :—

One litre of Water contains—	At 3 atmos.	At 1.5 atmos.	Taken with Mud when blowing off Boiler.
$Ca\ SO_4$ ($Ca\ O,SO_3$)	0·885 gram.	1·136 gram.	3·028 gram.
$Ca\ Cl_2$ (Ca Cl.)	1·008 „	— „	— „
$Mg\ Cl_2$ (Mg. Cl.)	3·479 „	0·189 „	0·769 „
$Na_2\ SO_4$ ($Na\ O,SO_3$)	— „	0·104 „	5·161 „
Na Cl.	4·743 „	0·478 „	9·582 „
Residue found on Evaporation	7·210 „	—	18·864 „

He shows that only a portion of the calcium sulphate in boiler incrustations contains water of crystallisation. In boilers which have been submitted to a very high pressure it occurs anhydrous. Magnesia exists as hydrate, the magnesium chloride giving up its hydrochloric acid under the influence of heat. The magnesium carbonate is decomposed at a temperature little above 100°, and magnesium sulphate undergoes mutual decomposition with calcium carbonate, the carbonic acid escaping. From a number of analyses given it is noticeable that the higher the pressure, and consequently the higher the temperature, up to 3 atmos., the larger the quantity of $2CaSO_4+H_2O$, in comparison with the $CaCO_3$. But, contrary to the opinions of many, Fischer holds that carbonate of lime suffices of itself, or probably also aided by silica, to form a hard crust.

It appears from analyses of marine crusts to be probable also that the quantity of Na Cl in the crusts increases with increase of the steam pressure under which these have been formed.

CORROSION.

From one or two causes, corrosion has been found to attack the exterior surfaces of boilers, and eventually to work considerable damage. This, however, is a simple matter, as the action in these cases is easily preventable.

Thus, in the case of land boilers, careless setting in too much lime has produced bad effects—the part of the boiler shell exposed to the probably impure lime having been eaten away to a large extent.

Setting the boilers upon a damp foundation without proper provision for

small transparent prisms coloured with carbonaceous matter. (Johnson, *Phil. Mag. J.* 13, 325 Also *J. pr. Chem.* 16, 100.)

		Calculation.	Johnson.
2 Ca O, SO_3	136.	93·79	93·272
HO	9.	6·21	6·435
Carb. matter	—	—	0·293
	145	100·00	100·00

draining, has also resulted in rapid destruction, whether the moisture reached the boilers through the lime of the setting or through the ashes.

Both marine and land boilers have been seriously corroded by ashes, when cold, having been carelessly allowed to remain in contact with the iron. The ashes contain a considerable quantity of alkaline salts of some strength; and with damp drawn from the bilge water in vessels, or from the ground ashore, or by deliquescence from the atmosphere, these salts have been enabled to attack the iron vigorously.

It has also been found by S. Dana Hayes (*Chem. News*, vol. xxx., 153, *Jour. Chem. Soc.*, vol. xiii., p. 294) that the soot in tubes and flues has become charged with pyroligneous acid, where wood has been freely used in lighting fires, or large quantities of coal have been charged at a time; and that this combination has caused corrosion. The same result has been caused by soot retaining fine dust of ashes, and in consequence also sulphur acids, derived from pyrites in the coal. A case of this kind is also published by J. W. Chalmers Harvey, in *Chem. News*, xxxii, 252; *Chem. Soc. Jour.*, No. clxi., p. 796.

It is sufficient, however, to point out these causes, for they suggest their own remedies. Care in preparing and completing the setting, in cleaning flues and ash pits, and in firing being all that is necessary to prevent corrosion from them.

The injudicious use of brass cocks and connections bolted or fastened directly to the boiler shell, has often resulted in corrosion from galvanic action at the places where the two metals come in contact. This action proceeds more rapidly when a little leakage of water takes place at the joint or connection.

The operation of corroding forces in the interior of boilers is, however, far more serious and baffling. Yet even these forces may be reduced to submission, but they demand study in the becoming spirit of patient inquiry.

Many investigations of these forces and their actions have been made, and it is advisable to review these before attempting to deal with the subject from an engineering point.

One of the first to publish experiments and trials connected with the corrosion of metals was the late Professor Crace Calvert, who exposed iron and steel (with other metals) to the action of sea-water, of natural fresh water, and of distilled water, with and without air. He also submitted iron and steel to the action of various gases, with and without moisture, and to that of various acids. In general, the results obtained by him showed that steel and then iron were most rapidly corroded by sea-water when simply immersed in the sea for a time. (105·31 grammes of steel and 99·30 of iron being dissolved from plates of forty centimetres square by immersion in the sea for one month.) Also that iron immersed in water containing carbonic acid oxidised rapidly with escape of hydrogen gas, which led him to suppose that some galvanic action had part in the operation. He may, however, have meant merely thus to designate the decomposition of a part of the water by which oxygen was dissociated and combined with the iron under the influence of the carbonic acid. The corrosive action of carbonic acid was corroborated by his experiments with gases, for when bright blades of steel and iron had been exposed for four months to the action of various gases he obtained the following results: There was no oxidation with dry oxygen; with damp oxygen, one blade only out of three experiments was slightly oxidised; no oxidation with dry carbonic acid; with damp carbonic acid there was a formation of white carbonate of iron on the blades; no oxidation with dry carbonic acid and oxygen, but very rapid oxidation with damp carbonic acid and oxygen. He also found that distilled water which did not contain air or gases was without corrosive action upon iron, a bright blade

which was immersed in such water having become in some days merely here and there spotted with rust. It was found that at these spots where oxidation had taken place, there were impurities in the iron which had induced galvanic action, "just as a mere trace of zinc placed on one end of the blade would establish a voltaic current."

An analagous action of distilled water with and without air was observed in his experiments with lead—200 litres of distilled water without air having dissolved during eight weeks only 1·829 gramme from a surface of 1 square metre, while the same quantity of distilled water when aërated dissolved in the same time 110·003 grammes.[1]

These investigations were made the basis of an inquiry by Mr. W. Kent, of the Stevens Institute of Technology, into the corrosion of iron in railway bridges in the U.S., and by their means he was enabled to arrive at a satisfactory demonstration of the causes of the action. His paper was published in the *Engineer* in Aug., 1875.

Recently, some of Calvert's results have been verified by A. Wagner, who publishes (in *Dingler's Polyt. Jour.*, 218.70-79) an important paper on the Influence of Various Solutions on the Rusting of Iron. Distilled water free from air does not appear to have been tested, but with air freed chemically from all carbonic acid, a slight rusting was noticed, the water, however, soon becoming saturated with its proper quantity of iron. The action of carbonic acid (or carbon dioxide) observed by Calvert is also noted, and the fact noticed for the first time that the presence of chlorides of magnesium, ammonium, sodium, potassium, barium, and calcium in the water largely increases the production of rust, while this important fact also appears from his results, that the corrosive action of all these substances is considerably increased by the presence of air and carbonic acid in solution. Chloride of magnesium of all these salts is the most active agent when alone in corroding the iron, but combinations of chloride of magnesium and carbonate of lime, of chlorides of barium and calcium, and of chlorides of sodium and calcium have also considerable corrosive action.

This to some extent corresponds with the fact observed by Mr. John Gamgee, as a difficulty which he had to encounter in connection with the continuous freezing of water for his "Glaciarium," viz., that the brine solutions used as media of congelation act destructively upon the metallic surfaces of the pipes or channels through which they are conveyed. (*Engineering*, vol. xxi., page 226.)

Wagner, however, has also noticed that while chloride of magnesium solution in the absence of air attacked iron at a temperature of about 100° Cent., the chlorides of sodium, potassium, barium, and calcium were without action under these circumstances. This author also notices the fact, the observance of which is ascribed to Mr. Young, of Kelly (in a paper read by Mr. James R. Napier before the Phil. Society of Glasgow, Dec. 16th, 1874), viz., that the presence of an alkali in water protects iron and prevents rusting. In consequence of the great importance of his results, I give two tables of figures (from the four contained in his paper) representing some of them.

[1] Sir R. Christison has made investigations into the action of water on lead (*Chemical News*, vol. xxviii. 15), but seems in his conclusions not to have distinguished between distilled water and pure natural waters, merely comparing them with respect to *purity*. Yet the fact that he always found carbonate of lead formed by the action of the purest waters suggests that the action was due to the presence of gases in solution, and not to the water itself.

No.	Solutions.	Percentage of loss of weight in 1 week.	
		With air free from CO_2.	With air and CO_2.
1.	Freshly distilled water	0·83	1·53
2.	Containing $Ba\ Cl_2$ and $Ca\ Cl_2$	1·63	1·46
3.	„ Na Cl and KCl ...	1·20	2·03
4.	„ $Mg\ Cl_2$	1·40	1·85
5.	„ $NH_4\ Cl$	1·29	2·16
6.	„ $K(OH)_2$	—	—
7.	„ $Na\ Co_3$	—	—
8.	„ Sea water	1·26	1·02
9.	„ Sea water evaporated and oil 5 drops ...	0·47	0·73

No.	Solutions.	Boiling in contact with air then and while cooling. Percentage of loss of weight in—					
		1 week.	2 wks.	3 wks.	4 wks.	5 wks.	6 wks.
1.	Distilled water	0·44	0.82	1·15	1·53	2·02	2·46
2.	Flask half-filled with distilled water—*i.e.*, more air ...	1·01	1·62	2·75	3·68	4·53	5·18
3.	Containing $Ba\ Cl_2$ and $CaCl_2$	0·66	1·33	1·57	1·82	2·03	2·27
4.	„ Na Cl and KCl ...	0·84	1·47	2·15	2·57	3·04	3·41
5.	„ $Mg\ Cl_2$	1·31	1·91	2·20	2·49	2·76	3·05
6.	„ $Mg\ Cl_2$ and excess of $Ca\ CO_3$ ...	0·89	1·54	2·08	2·46	2·97	3·27
7.	„ $NH_4\ Cl$	1·15	1·86	2·56	3·16	3 66	4·16
8.	„ $K(OH)_2$	—	—	—	—	—	—
9.	„ $Na\ CO_3$... ...	—	—	—	—	—	—
10.	Sea-water	0·43	0·65	0·70	0·75	0·97	1·24
11.	Sea-water and $Ba\ Cl_2$ ...	0·15	0·46	0·69	0·92	1·08	1·23
12.	Sea-water and 10 drops oil	0·59	0·59	0·62	0·72	0·83	0·93

I quote here an important experiment made by him on the effect of chloride of magnesium on iron at boiling temperature.

Two grammes of neutral magnesic chloride were introduced into a strong tube, in which weighed pieces of iron were placed; boiling distilled water was added, and the tube sealed up while steam was issuing. It was then kept at 100° Cent. (212° F.) for six weeks, and after cooling was opened. Gas was evolved on opening it; the iron was black, and had lost 0·39 per cent. in weight, and the solution, when filtered, contained chloride of iron (ferrous chloride). (*Dingler's P. J.*, ccxviii. 70-79. *Chem. Soc. J.*, No. clx. p. 522.)

Still another valuable contribution to our knowledge of this subject comes to us from Germany, in the results of an examination of the effects of condensed water containing grease on boilers which were fed with it, by Stingl, an author who also proposed and successfully carried out a method for the purification of that water.

The water was evidently condensed by means of an injection condenser, as salts of lime and magnesia were present in small quantity in the condensed water. These salts, in presence of grease, at a temperature not exceeding 60° to 70° C., form lime-soap—part of the lime-salts being, as has already been shown, rendered insoluble at these temperatures. The lime-soap, under the influence of a higher temperature, partially decomposes into free fatty acid and an organic substance which is reducible by further heat, yielding a carbonaceous residue. This substance is a kind of basic lime-soap which adheres to the boiler surfaces, while the acid, which is usually oleic acid, attacks and dissolves the iron. In the crust the fatty acid is recognised by the addition of hydrochloric acid, the separated organic mass being afterwards shaken with ether. The boiler crusts have usually a dark colour, partially due to the presence of oxide of iron, partly to separation of carbon from the fatty acid partially decomposed. Even if lime and magnesia salts are present in very insignificant proportion, the presence of grease is none the less injurious, as with saponification under great pressure, a very small quantity of lime suffices to occasion the splitting up of a neutral fat into free fatty acid and glycerine; with low pressure it is not doubted that the same decomposition occurs, though more gradually.

A sample of very soft water (6° of hardness) depositing very little crust was submitted to the author of that paper, as a boiler in which it had been used was completely destroyed after three years' work. This water had a milky appearance, and contained 0·212 part of fat in one litre.

He also quotes the case of the corrosion of a gasometer, the cistern of which had been luted with greasy condensation water. The gasometer would have lasted 20 or 30 years had ordinary water been used, but in the circumstances mentioned, that part of it exposed to the water was corroded through after four years.

The destructive action of the oleic acid on the oil-pumps used in stearin candle manufactories is also alluded to. And the following details are given of an interesting case of boiler corrosion, with accompanying incrustation, and of the means used to overcome the destructive action. The condensed water from two steam engines, respectively of 300 and 100 horse-power, was used to feed a steel boiler of the Cornish design. After only three weeks' firing, water began to leak into the tubes, and shortly after the boiler had to be stopped for examination and repair. A deposit on the upper part of the tubes, from 8 to 11 mm. thick, was found. The water had an opalescent appearance, at once removed by ether, which the author recommends as a good qualitative test for the presence of grease in water. The following is the result of analysis of the condensed water, which was obtained at a temperature of 40° to 50°.

	In 10,000 parts.
Calcium carbonate	1·3091 „
Magnesium carbonate	0·6930 „
Calcium sulphate	0·3158 „
Magnesium chloride	0·0134 „
Sodium chloride	0·1200 „
Ferric oxide and alumina	0·0241 „
Silica	0·0023 „
Organic matter	0·4138 „
Total	2·8915 „

The crust deposited from this water had a dark greyish-brown colour and was friable; but when pulverised it was difficult to wet with water. It effervesced strongly with hydrochloric acid, a black fatty mass being left floating on the surface of the acid, which, shaken with ether, yielded thereto about 5·19 per cent. of a brown oil. The residue, insoluble in hydrochloric acid, was washed with ether to remove fat, dried at 100 deg., weighed and ignited. The following shows the full analysis:—

Calcium carbonate	51·42 per cent.
Magnesium carbonate	11·30 „
Magnesium hydrate	3·90 „
Calcium sulphate	6·63 „
Ferric oxide	12·75 „
Alumina	0·31 „
Silica	0·34 „
Fat acids	5·19 „
Combustible matter	8·46 „
	100·30

In order to purify the water, the calcium carbonate and part of the magnesium carbonate, with all the grease, were removed by precipitation and subsequent filtering. The fat particles were removed by being enveloped by the precipitated calcium carbonate, which mechanically retained them on the filter, the reaction being favoured by suitable temperature and intimate mixture previous to filtering.

The water then contained in	10,000 parts.
Calcium carbonate	0·1773 „
Magnesium carbonate	0·4135 „
Calcium sulphate	0·2068 „
Magnesium chloride	0·0108 „
Sodium chloride	0·2351 „
Silica	traces.
Ferric oxide and alumina	traces.
Organic matter	0·1512 „
Total	1·1947 parts.

No grease could be detected in the filtered water, which was then used in the same boiler, after being repaired, for three months, when the deposit on the tubes was found to amount to a layer of only the thickness of a sheet of paper and almost wholly consisted of gypsum, and easy to remove. The

whole amounted to only 5 kilos. in weight after 3 months' steady work. It was a loose greyish-brown mass, the following showing the analysis :—

Calcium carbonate	19·30 per cent.
Magnesium carbonate	1·26 „
Magnesium hydrate	45·02 „
Calcium sulphate	15·12 „
Ferric oxide	9·43 „
Silica	2·04 „
Organic matter (insol. in ether)	7·35 „
Fatty matter	traces.
	99·52

To purify such water as the above named for high pressure boilers, a mixture of lime-water and caustic soda solution is recommended, as this not only removes fat acids but also removes the magnesia, which forms, with gypsum, hard incrustations at high temperatures. (*Dingler Polyt., J.*, ccxv., 115-121 ; *Chem. Soc. J.*, vol. xiv., sec. 2 p. 132.)

In a letter on the corrosion of boilers, addressed by me in October, 1874, to the Editor of *Engineering* (and published in that paper on October 23, 1874), reference was made to the Report on Corrosion of the Tubing of two of Rowan and Horton's Patent Boilers, by Mr. Thomas Spencer, an analytical chemist. Starting from the slender basis afforded by the examination of water mains in two cases of internal corrosion of these, where a very pure natural water was conveyed through them, Mr. Spencer argued that the corrosion in these boilers was due to the use of distilled water, which alone was used in them, but which he confounded with pure natural water. In the absence of any well ascertained facts as to boiler corrosion, his opinion was accepted as sufficiently explanatory of the action ; but, as is often the case with half-knowledge, that which was true in his investigations was rendered indistinct by crude conjectures. In consequence of this, in the letter referred to, and generally in all published opinions emanating from engineering sources which I have seen, neither the great difference between genuine distilled water and pure natural waters—viz., the quantity of air and gas which is invariably held by the latter—has been properly weighed or even acknowledged, nor has the only point of similarity between the distilled water from surface condensers known on board steamers and pure fresh water—viz., that there is always some air present in the former—been noticed or allowed for. In the letter referred to, I regret that I also confounded distilled water with Loch Katrine water, through having in view merely purity, and not considering the presence of air or gases.

In considering now some examples of boiler corrosion, I shall adopt the arrangement already used in the section on Incrustation, viz. :—

1. Land boilers using natural fresh waters ; and,
2. Marine boilers.

1. From what has been before us in connection with Incrustation, it is plain that it is only in those land boilers which are fed with pure natural waters that we are likely to find Corrosion at work. Where lime salts are present, a crust is formed, and the metal surfaces of the interior of the boiler are thus kept from contact with the water and any corroding ingredient in it. The special inconveniences of such crust formation we have already considered. Highly chalybeate waters, although not depositing a crust, do not seem to act injuriously. A case is mentioned in Mr. James Napier's paper in *Proc. Phil. Soc. G.*, demonstrating this. There may, however, be some material forming part of the crust, or adhering to it, which suffers decomposition in contact with the heated iron, and, as a consequence, attacks the

metal. This is the case with crusts formed with fat or greasy substances, as in the instance already quoted in the paper by Stingl.

We have, in this district, ample opportunity of proving the effect of very pure fresh water upon boilers, because there are few natural waters of greater purity than that from Loch Katrine, with which various manufactories in and around this city are supplied.

The water formerly supplied to Glasgow having been calcareous, it has been found that boilers which used it for some time have not suffered from corrosion when subsequently fed with Loch Katrine water—the explanation of this being the fact that the thin coating of lime which these boilers had acquired acted as an efficient and permanent protection.

Where, however, owners or managers have been very zealous in removing by mechanical or chemical means every trace of that crust in order to get the full benefit, as they have thought, of the pure water, the result has been different and the "full benefit" has often been of a kind to perplex them. When also new boilers have been started from the first with Loch Katrine water, corrosion has been more or less rapid, and considerable trouble and inconvenience have been caused thereby.

These facts find illustration in many manufacturing establishments around. I have been informed, amongst others, of a boiler attached to a mill in Bridgeton, where every care was taken to remove all scale before introducing Loch Katrine water, and the millowners were chagrined by finding their boiler quickly suffer from corrosion.

In an engineering work at Port Dundas, one boiler which had wrought upon a supply of the former calcareous water, and was latterly supplied with Loch Katrine without being scaled, continued to work for some years without showing symptoms of distress from corrosion. In the same works, however, a range of new boilers, put down after the introduction of the pure water, suffered so severely as to require constant repairs at tubes, and an entire new set of tubes (of between 40 and 50 in each boiler) in a comparatively short time. In another engineering work on the south side of the city, the main shop boiler was worked for three or four years without suffering corrosion with Loch Katrine water, after having worked previously for seven or eight years with the former Glasgow water. When a new boiler was substituted for this old one, although the new one was subjected to precisely the same conditions as those its predecessors wrought under for some years without trouble or difficulty, it was found to the consternation of the proprietors that the new boiler was corroding away so fast as to suggest that a third boiler would be required very soon. Until the presence and effect of the lime coating in the former boiler were pointed out, it was impossible for them to understand how one boiler should be able to use Loch Katrine water without damage, while another similarly worked should suffer in so short a time.

In the former of these two examples no condensed water was fed into the boilers, as they were working in connection with high pressure atmospheric engines and other machines; consequently there was no grease or other corrosive agent introduced into them, and thus the corrosion could be traced directly to the water. In the latter one, a part of the condensed steam was collected in the feed cistern, and a considerable quantity of grease thus found its way into the boiler, thus aiding the corrosion somewhat. Steps were at first taken to exclude this grease from the boiler, but the corrosion afterwards proceeded—large quantities of oxide of iron being removed from the boiler—until means were adopted to overcome the action.

The following is the result of the analysis of the water made during July, and published by Professor Mills, who informs me that it represents a fair average of the quality of the Loch Katrine supply.

	In 100,000 parts.
Total solid impurity	3·16
Organic Carbon	0·110
Organic Nitrogen	0·033
Ammonia	—
Nitrogen as nitrates and nitrites	—
Total combined Nitrogen	0·033
Chlorine	0·70
Hardness	0·48

The report also bears that the water was pale brown in colour and contained traces of fibrous matter and muddy particles, and that the general condition was very satisfactory.

Nothing contained in the water as impurity can account for its destructive action ; but the fact that it contains 7 to 8 cubic inches of gas (of which about 3 cubic inches are oxygen) to the gallon in solution, coupled with the investigations already quoted in this paper, as to the effect of distilled water without gas and of water containing gas, makes all plain. The corrosion is due to the action of the carbonic acid and oxygen held by the water, and the action is all the more rapid, from the absence from the water of any mineral matter with which the gases can combine. In both of these engineering works an artificial coating of lime was formed in the interior of the boilers, by feeding regularly into them each morning for some time a whitewash of Irish lime and water. This expedient was quite successful in checking the corrosive action, and as the lime soon hardened, under the influence of the heat, no trouble was experienced in preserving the coating. Pieces of limestone were also placed in the feed tank or cistern, but it is doubtful if they produced much effect. Where, however, it is possible to mix with Loch Katrine or other pure water, a proportion of a calcareous natural water for a time, the scale formed thus in working will probably be of a more enduring nature. I strongly recommend this plan to those using Loch Katrine water who have access to former sources of supply.

2. Marine Boilers.—We are introduced to a variety of corrosive actions, in considering marine boilers, according as we have to deal with boilers working with nothing but fresh water or those which use a proportion of sea-water. It is necessary, however, clearly to distinguish these two classes

The only marine boilers as yet using exclusively fresh water, in regular working, with which I am acquainted are those of Rowan & Horton, mentioned in the letter to *Engineering*,[1] to which I have referred, and elsewhere, and those working on Perkins' plan. Some of the ordinary boilers used in steamers with what are called compound engines, have been occasionally wrought entirely with fresh water, but in every such case recorded, that manner of working was abandoned after a very short trial, in consequence of the rapid corrosion which was discovered to be going on. Boilers in vessels whose voyages are always made in sea-water, are constantly liable to receive a small quantity of salt water by leakage through surface condenser joints, or some other connections, so that even where it is or has been the intention to use fresh water only, it is not possible without analysis to determine if that has been done. The first of the examples quoted above have, however, this element of uncertainty removed from their case in consequence of their steamers running in fresh water, except for a very small part of their voyage. In their case corrosion from fatty acids and from galvanic action, of what may be called an intermittent kind, was experienced and successfully counteracted. These actions, and the respective remedies which were adopted, I have mentioned in the published letter referred to,

[1] This letter is printed at the end of this paper.

and I quote them here because they show what are the corrosive forces to which marine boilers, working exclusively with fresh water, may be subjected. Lime was present in small quantity in the river water used to fill up the boilers at starting and to make up waste in working, so that the decomposition of fats already described could take place. When the grease was removed as much as possible by filtering the feed water, and the presence of any free acid was neutralised by zinc, the corrosion ceased. The galvanic action was also arrested by means of the filter, because in general this action was caused by local contact with particles of metal carried into the boiler, and not, as has been erroneously supposed, by means of the surface condenser and the boiler forming together the two elements of a huge battery, the steam and water being the exciting medium.

Of Perkins' boilers worked in steamers we have no published accounts with which I am acquainted, so that we cannot say whether they have suffered from corrosion in the course of the exigencies of practical voyage making. It is, I know, the aim of Mr. Perkins to exclude, if possible, all sea-water and all oily matter from his boilers, and if successful in doing this, and working only with fresh water, the corrosion will not be great. Still, there will be some, as the gases of the natural fresh water with which the boilers are filled at starting will oxidise their proportion of iron, and in the feed water, which, as condensed steam, has been returned from engines through the surface condenser and discharged by the air pump into the hot well, there is of necessity (probably not much), yet some air present, as the condensation takes place in contact with air ; and this air will also do its own share in corroding fresh portions of the clean surface of the boilers. It is probable that if these boilers are introduced into merchant steamers and become subject to the invariable emergencies of regular trading, by which leakages, deficient supply, and contamination of feed water are experienced, and foreign substances find their way into the boilers, the evils of corrosion may be known to a greater extent than that to which they reach where it is possible to observe all the precautions of the inventor of that system.

Generating steam from fresh water alone is undoubtedly the proper, as it is sure on this account to be ultimately the general, mode of operation with steam boilers, but for ordinary sea-going purposes, appliances must not be too delicate, but require to possess the power to endure abnormal and adverse conditions.

The case of a coasting steamer using in her boilers natural fresh water from two sources (one at each end of her voyage) whose boilers were destroyed by corrosion with great rapidity, was made known by Mr. James Gilchrist, in a paper read before the graduate section of the Inst. of Engineers in Scotland, and published in February of this year in a periodical called *Marine Engineering News*. Analyses of one of these waters (the other having been Loch Katrine) and of the deposit found in the boilers are given in the paper, with the opinions of two professional chemists, who ascribed the corrosive action to the injudicious use of a large quantity of tallow in engines and boilers. There is no doubt that the decomposition of the tallow was in i self sufficient to cause serious damage to the boilers in presence of fresh water containing a small quantity of lime ; but the action in this case was modified by a fact not noticed by the chemists—viz., that during the voyage of the steamer all deficiency in feed water was made up from the sea. The boiler deposit consequently contains 9·11 per cent. of magnesia, and ·12 per cent. of common salt, as well as 8·86 per cent. of oil and organic matter ; and it is to the presence and decomposition of chloride of magnesium to which the presence of magnesia in the deposit bears witness, as well as to the carbonic acid of the original boiler supply, that a great part, and probably the rapidity, of the corrosive action is, I believe, to be attributed.

This leads to the consideration of marine boilers using partly fresh and

partly salt water, by far the most extensive class at present, and that which has suffered most from corrosive action.

A very intelligent account of the state of matters in this class of boilers is given by Mr. Milln, in a paper read before the Cleveland Iron Trade Foremen's Association, Nov., 1875, and published widely in the engineering periodicals. This author describes graphically the introduction of the surface condenser into marine engine practice, with which is coincident the commencement of all real trouble from corrosion, and he then describes the course of events with two distinct sets of marine boilers. In the first of these we have a good example of boilers which had been worked at comparatively low pressure viz., 25 lbs. per square inch and fed for four years with sea-water—working during that time in connection with an ordinary injection condenser attached to engines which indicated 900 horse-power. As the voyage was not of long duration and time was given for regular "scaling" of the boiler surfaces (*i.e.*, removing the scale from them) at the close of every voyage, no damage was done by incrustation and no inconvenience beyond the cost of fuel consumed was experienced. The injection condenser was then replaced by a surface condenser, some of the old incrustation being left adhering to the boiler surfaces, and the boilers were worked for some time thereafter with fresh water, the deficiency in feed supply being made up from the sea. The crust was soon removed and the boilers corroded, showing pits and blotches and all the usual symptoms.

The other instance quoted by Mr. Milln is that of a new set of boilers working at 65 lbs. pressure in connection with compound engines of 1700 horse-power and surface condenser, evidently an excellent example of average modern steamship machinery. These boilers were worked from the first with fresh water, the waste being supplied by distilled water, yet the density of the water increased daily and corrosion proceeded at the same time most energetically. After one voyage the boilers were filled at starting with sea water, but no more sea-water was added during the voyage except the small quantity necessary for surplus feed supply. Under these fresh circumstances corrosion still proceeded, though it was thought more slowly, and was only finally stopped by what is called "changing the water," *i.e.*, blowing off a quantity regularly and replacing it with sea-water, thus introducing fresh quantities of sea-water into the boilers during the voyage.

This author then alludes to the many theories explanatory of corrosive action which have been started, but only to reject them all and adopt the popular error, that corrosion is due to a change supposed to be wrought upon the water itself by distillation or re-distillation, which, according to some, confers upon it the properties of a powerful solvent of metals, and according to others, although they do not like to state it thus plainly, this distillation decomposes the water and dissociates its oxygen, which forthwith attacks the iron of the boilers, or as Mr. Milln puts it: "the constituent elements of water when frequently re-distilled undergo such a change as to greatly intensify its action on or affinity for iron." One engineering journal indeed very confidently affirms that it is "a fact but too familiar to engineers that the continuous boiling of distilled water in an iron vessel causes the destruction of that vessel," but has to admit that the circumstance that that water also passes over a very great surface of brass or copper (of the destruction of which, however, not a word is said) complicates the aspect of the phenomena.

It must, however, be confessed by engineers, that of the data or investigations by which so apparently wild a theory has been established as a fact they are as yet profoundly ignorant, and as Mr. Milln observes, "it is with regard to the nature of this change that we so much want information!" There is this solitary fact known and harped upon, viz., that dry steam in contact for a period of time with iron or carbon, in a tolerably fine state of division and at a red heat, is decomposed, hydrogen gas escaping, while the

oxygen combines with the iron or carbon. But this has never been attempted with water nor can it be done with steam below red heat. What is known of the action of distilled water proves, indeed, the clean contrary to this theory, and in illustration of "what is known," I refer to those investigations which I have already quoted. They prove that it is the presence of air or gases which makes the difference in the action of various pure waters, and even in that of the various salts dissolved in impure waters, and that when water is distilled free from air, its corroding power is lost. Thus the remedy for corrosion proposed by some engineers to-day, viz., that the condensed steam should be aerated, proves to be a foolish suggestion, for this would but increase the power of that water to corrode the iron of the boilers.

I shall be within the strict truth when I say that it is hasty to conclude, from examples of boiler corrosion, that distilled water has to do with the corrosion, for the fact is that there is no case known in which the proper effects due to the employment of distilled water alone, and free from gases, upon the metal of boilers, could have been observed. The boilers of Rowan and Horton, and of Perkins, present the nearest approach to the conditions requisite for such information, but not all the necessary conditions are found even in these instances. The examples just quoted from Mr. Milln's paper are of the kind with which engineers are more generally familiar, and they do not give such data as would lead to the conclusion about distilled water. The opinion is therefore due to a hasty conclusion, drawn from the coincident occurrence of corrosion with the introduction of surface condensers.

In the first example, genuine distilled water was never present. The boilers were filled up with fresh water at starting with the surface condensers, but not only was waste and deficiency of feed made up from the sea during the voyages, but there was also the saline crust adhering to the boilers to be dissolved or partially dissolved by the fresh water. Contrary to the opinion of Mr. Milln and others, I maintain that just because analysis shows that such crust contains chloride of sodium (in appreciable quantity when formed at such a pressure as that of the boiler mentioned—viz., 25 lbs. per square inch), if not also other soluble ingredients, a certain part of the crust must have been—and in such cases always is—dissolved; and thus the crust is partially disintegrated, and the insoluble magnesia and sulphate of lime fall in flakes to the bottom of the boiler. The fact that the water did not long remain fresh does not in any way interfere with this opinion, for it is a fact well known that salts dissolve more readily in a solution of other salts than in fresh water. Hence the scale would come off even more rapidly when a small quantity of sea-water was used.

The second example started with boilers filled with natural fresh water, which itself has (as we have seen), if pure, power to corrode by its gases in solution; but although distilled and not sea-water in this case was used for surplus feed supply, the salinometer test showed plainly that pure distilled water was never present, and that either sea-water was getting in through a leaky condenser, or that fatty and other matters were accumulating in the boiler, the colour and taste of the water being decided indications that such (and probably both of these) results were happening. After the first voyage which gave such results, sea-water was regularly used in greater or less proportion.

Thus we must search for the corroding agents apart from the distilled water. The analyses by Dr. Wallace and others, of boiler crusts, and the researches of Wagner and Fischer quoted herein, reveal one very important one, viz., the chlorine or hydrochloric acid set free by decomposition of the chloride of magnesium in the sea-water. This decomposition may take place under the influence of high temperature alone, when magnesium hydrate is deposited, while the iron is attacked by the hydrochloric acid, first

chloride and subsequently oxide being formed. As the combined influences of temperature and carbonate of lime are present, it is probable that the sulphate of magnesia is also decomposed, and that some oxychloride of magnesia is also formed, but this has not yet been demonstrated by analyses of deposits, though it is the opinion of Dr. Mills and others that part of the magnesia reported in ordinary analysis of boiler deposits from sea-water exists in that form. Dr. Fischer also demonstrates that this mutual decomposition of magnesium sulphate with calcium carbonate is a fact, and that the liberation of carbonic acid also necessarily takes place.

The researches of J. Y. Buchanan "on the power of sea-water to absorb carbonic acid," to which I have already referred, have shown us that sea-water, on account of the sulphates which it holds in solution, absorbs a large amount of that gas, which it readily gives up on the sulphates being decomposed or separated from the water. Such decomposition and precipitation of sulphates occur in marine boilers, besides there being, now since the surface condenser era, repeated boiling of the water, which of itself in time liberates nearly all the carbonic acid. We have in these two agents, viz., the hydrochloric acid of the decomposed chlorides and the carbonic acid, combined with high temperature and pressure, quite enough to account for most of the corrosion which occurs.

The researches of Stingl, which I have quoted, show the power for evil which greasy matters wield, and this specially I believe where the water is comparatively fresh, though not there alone. And where grease is allowed to reach the boilers it can also carry along with it particles of other metals, which, in spite of the incredulity of some engineers, have been found to do mischief, and are capable of doing, if possible, more in presence of salt water than with fresh, unless it be acidulated. It is not supposed that they can do all the mischief, or even any in places to which they cannot reach; it is sufficient that they are capable of doing some, and there are specimens extant (among the specimens collected by the Admiralty committee on boilers for instance) of corrosion and abrasion of brass tubes and other parts of engines, which show that this is a real and not a fancied danger.

The simple explanation of the fact that all such corroding agents have done damage principally since the introduction of the surface condenser, is that the surface condenser, by separating the condensed steam from the sea water used to condense it, and by returning so much fresh water to the boilers, has reduced the proportion of sea-water used in them below that point at which it is possible to form a protecting scale or crust by the saturation of a considerable quantity of sea-water. It also, as I have said, provides for the complete liberation, by repeated boiling, of the carbonic acid held by the sea-water.

That sea-water alone at the boiling point corrodes iron is proved by one of Wagner's experiments, in which the percentage of loss from a piece of iron plate which was kept in contact with boiling sea-water and air for six weeks, steadily increased from 0·43 per cent. after one week to 1·24 per cent. after six weeks. And proof that in marine boilers a small proportion of sea-water is capable of doing mischief while a large quantity is not, is found readily in the fact that engineers have repeatedly *arrested corrosive action* by simply increasing the quantity of sea-water in the boilers, but without altering any of the other conditions of working. It is always in boilers that are "worked fresh" (*i.e.*, with the minimum of sea-water) that corrosion proceeds most rapidly, and I know of one steamer (the s.s. Vespasian) where by continually working fresh, a new set of boiler tubes was required in little more than twelve months after starting, while after that time, in the same boilers, the use of a large proportion of sea-water was enough, without further change in working to preserve the boilers from rapid corrosion. As soon as the smallest quantity of scale begins to form, destructive action is arrested.

This is true of all the various kinds of destructive action, and explain's how under the old régime none of these were known. It also shows how fallacious must be any conclusions drawn from comparisons of results with old boilers in any attempt to argue from them to results in modern ones, as though both were obtained under like conditions. Another proof of the existence of such decompositions as I have described is found in the fact that the water of boilers in which corrosion is going on becomes alkaline. This shows an accumulation in solution of the effect of the alkaline ingredients of sea-water, by decomposition and the neutralisation of the acid ingredients, and it is for this reason that some have been disappointed by testing the water, who had concluded that if corrosion was due to the presence of acid substances then the water must be acid.

The pitting and blotching effects produced on the metal of the boilers prove on examination to be not so mysterious as our first apprehensions render them. The same results follow the use of corroding liquids in any metal vessels when exposed to air and to sight. Even basins made of platinum—which is harder and closer in texture than any other metal—I am informed, are found by chemists to wear in a similar way by having certain liquids boiled in them, and thus the effects are apparently due to non-homogeneity of the metals as well as to purity in some cases. Heat in most instances has a considerable share in directing the action, which is usually found to have been more intense in the hotter regions.

Before adverting to a remedy for this action, I may say that in the boilers of the s.s. Propontis, analyses of crusts from which are given at page 613, the various results of corrosion were experienced. Increase of density in the water observed when nominally working with fresh water alone proves, from the analysis of the deposit then taken from the boilers, and from an estimation of the total solids in the water at the close of that voyage (made by Mr. Tookey, and found to amount to 3272·5 grains in the gallon), to have been due to leakage of sea-water into the boilers by means of connections with a small boiler used for supplying steam to a cylinder steam-jacket. Milkiness and acrid taste in the water were no doubt due to the presence of fatty substances in solution, as a large quantity of grease was collected on the filter through which all the feed water passed. It is probable that these two causes will be found to account in nearly all cases for the increase of density often observed in similar circumstances of working.

It now remains to suggest a remedy. Much has been said in favour of the use of zinc in boilers, but zinc will not do where any proportion of sea-water is used, because it is very rapidly decomposed by the salts in sea-water, and chloride of zinc merely adds to the impurities and evils of the case. It has been, and may be, used successfully in fresh water, where there is free acid to be neutralised, but there its usefulness stops as far as corrosion is concerned.

Filtering the feed-water is a most excellent precaution, and should undoubtedly be universally adopted in order to prevent, as far as possible, the entrance of foreign substances into the boiler.

To prevent the corrosive action in them of matters in solution, which no filter can arrest, I believe no better remedy can be found than the forming on the interior surfaces an artificial coating composed of calcium sulphate and magnesium hydrate in proportions varying according to the pressure carried in the boiler. This can be readily fed in, in the form of a thin whitewash, with fresh water, and should be applied to all boilers on the very first occasions of getting up steam in them. Otherwise corrosive actions may commence, and unfit the surfaces for the adherence of such a protecting crust. A protecting crust has repeatedly been formed in boilers by using salt water; and in one of Mr. Milln's examples he was able to keep this of proper thinness by regularly blowing off about 1-9th of the water evaporated

Yet this is, as he admits, a very troublesome, and not a safe method of working, and yet to keep such a scale on, it must be carefully carried out without intermission, because as soon as the boilers are allowed to "work fresh" that scale dissolves off. By making an artificial scale with fresh water, as suggested, its thickness is quite under control, and when once hardened by heat, fresh water will not dissolve it, and thus steam can be generated in the best way. Even if a small quantity of sea-water should leak in it is not likely that the coating would be injured.

Apart from such a plan there seems to be no hope of escaping corrosion and advancing at the same time in engineering practice, until it is possible to have copper boilers. And yet, even then, as the recent experiments of Carnelley on "The Action of Water and of Various Saline Solutions on Copper" (*Chem. Soc.* J., No. clxiii., page 1,) seem to show, we should still have to combat the same difficulties.

THE WEAR AND TEAR OF BOILERS.

From *The Engineer*, Sept. 15th, 1876.

MR. F. J. Rowan, of Glasgow, has within the last few days read a paper in the Mechanical Section of the British Association "On Boiler Incrustation and Corrosion." Mr. Rowan's reputation as an engineer is a sufficient guarantee that a paper from his pen on such a subject will be worthy of consideration, and we regret extremely that he has requested us not to reproduce his contribution to Section G in a complete form. It is so compact, and yet so involved, that it would be impossible to condense it, and at the same time render intelligible the statements and the arguments which it contains. We have no course left open to us, therefore, but to call attention to the fact that Mr. Rowan has contributed some valuable information to the existing stock of knowledge concerning the wear and tear of steam boilers, and to give here some idea of the line of argument which he has adopted. The great defect of the paper is want of lucidity. Mr. Rowan publishes facts, opinions, the results of experiments, and the theories and explanations of a whole host of authorities, British and foreign, without much attempt at arrangement; and, unfortunately, he does not draw his deductions with the clearness which is desirable, while he has omitted certain extremely important considerations. It follows that the paper must be read, or rather studied, with a great deal of care before we can arrive at any definite conclusion as to Mr. Rowan's meaning; but, on the other hand, when we have found out what this is, we admit readily that his reasoning is sound as far as it goes, and in some respects novel, and no one will dispute that the paper has been prepared with great pains, and that it displays an extraordinary amount of special erudition on the part of the author.

Mr. Rowan first considers the causes and effects of incrustation in boilers, and we find with regret that while he repeats a great deal that has been said by Dr Rogers, of Madison, U.S., concerning the conducting power of incrustations of lime, etc., he has entirely ignored the fact that the conducting power of a body is practically no measure whatever of its powers of transmitting heat. It has been shown long since by Péclet, whose views have been endorsed by Rankine, that the ability of a plate of any substance to transmit heat depends far more on what has been termed the emissive and receptive powers of the two surfaces of the plate than on anything else. Thus, for example, an iron plate will conduct about twelve times as much heat in a given time as its surfaces can absorb or give out. The principle has been utilised by the employment of "heat pegs," or pins traversing the thickness of a boiler. All the heat which a surface of 12 in. can absorb is freely

transmitted through a single square inch of sectional area where the pin passes through the plate. That is to say, if we have a pin 1 in. square and about 6 in. long inserted in the side of a fire-box, so that something less than 3 in. of the length of the pin are in the furnace and the same length at the other side of the plate in the water, then the portion of the pin in the fire cannot be unduly heated, the sectional area of the pin sufficing to convey the whole of the heat absorbed and given out by the much larger surfaces in the furnace and the water. From a neglect of this fact Mr. Rowan tacitly admits that with half an inch of scale on a plate, that plate can be made red hot, or nearly so ; and he also accepts the statements of Dr. Rogers, to the effect that a scale of $\frac{1}{16}$ in. thick, increases the consumption of fuel by 15 per cent., while, when it is $\frac{1}{4}$ in. thick, 60 per cent. more fuel is needed. These statements we believe to be extremely incorrect. It has been shown, indeed, that the presence of a thin scale has actually increased the steaming power of a boiler, simply because the surface of the scale emitted heat more freely than a surface of iron to the water with which it was in contact. In several instances Mr. Rowan accepts statements which refer to isolated experiments, or the deductions of comparatively unknown experimentalists, with the same readiness and good faith. This is a serious defect in so elaborate a communication ; and we call attention to it in no unkindly spirit of criticism, but in the hope that when Mr. Rowan reprints his paper, as we believe he proposes to do, he will revise it in the sense of explaining to his readers whether he does or does not hold that such reasoning, as that of Dr. Rogers for example, is sound.

When we come to speak of the way in which Mr. Rowan has dealt with the chemistry of incrustation, we have little to say that is not praise. Never previously, we venture to affirm, has such a complete *resumé* of the opinions of chemists been placed before the world in compact form. We shall make no attempt to reproduce this portion of the paper, but hasten at once to say that Mr. Rowan's grand panacea for all the ordinary forms of incrustation is the use of soda ash. The quantity of this material used in a pair of boilers at Barrowfield—one 6 ft. 6 in. by 21 ft., and the other 7 ft. 6 in. by 27 ft.—is 6 lb. per week in both boilers. The total quantity of feed used is 9700 gallons per week. The soda is dissolved in water and pumped into the boilers, which are blown out once every three months. The deposit consisted, before the use of the ash, of carbonate of lime 66 per cent., with quantities varying from 1 to 8 per cent. of magnesia, sulphate of lime, silica, oxide of iron, etc. The soda ash has answered perfectly in this case, it would appear. As regards marine boilers, Mr. Rowan admits that soda ash cannot be used, and that the only true remedy for incrustation at sea lies in the use of fresh water. It is a remarkable fact that he passes over in silence the well-known truth that the deposit of lime salts in a boiler is due to the circumstance that these salts are less soluble in hot water than they are in cold water. If this were not the case, as we never have feed-water in the condition of a really saturated solution of carbonate or sulphate of lime, incrustation could be wholly avoided by blowing off. On the other hand, if water be heated to 212 deg., or a little over, before it is pumped into a boiler, and time be allowed for the settlement of the salts which it will then throw down, incrustation may be very nearly prevented. It would be entirely prevented, but that when the water is raised a second time in temperature in the boiler, a further quantity of salts becomes insoluble ; which is to say that that which just before was not a saturated solution because its temperature was 212 deg., now becomes one because its temperature is 280 deg. or 300 deg. We have never yet heard the truth of these statements controverted ; and they bear so important a relation to the question discussed by Mr. Rowan that it is to be regretted he has passed them over in silence.

Mr. Rowan's conclusions concerning the cause of corrosion in marine boilers will hardly be accepted without question by engineers. He arrays,

it is true, an army of authorities on his side; but as these men are for the most part chemists who have dealt on a very small scale with pieces of iron and various solutions, and have had no practical experience with steam boilers, we must refuse to believe that they have placed the solution of a very complex problem at the disposal of the world. Mr. Rowan's theory is, that the corrosion of marine boilers working with surface condensers is due to the presence in the water of grease, and some gas. He is not very particular what gas. To prove this theory he cites the experiments of Stingl, Wagner, Fischer, and others. There is nothing novel in the statement that the presence of grease in a boiler causes corrosion; but we believe that very many engineers will join with us when we assert that the most elaborate systems of filtering feed-water, and so excluding grease, have totally failed to prevent the decay of marine boilers. In fact, the presence or absence of grease has had, in a large number of instances, no appreciable effect one way or another on the decay of iron plates, and at this moment it is largely exaggerated. We do not dispute, however, that in several instances there has been some reason to think that grease had an injurious effect, and it is highly desirable for this and for other reasons to keep it out of a boiler. As regards the theory that the presence of air or some other gas sets up and maintains corrosion, we may say that, although the theory is not new as regards air, it appears to be quite novel as regards other gases. At least it is now put before the world in a complete and specific form for the first time. It is almost as difficult to prove that Mr. Rowan is wrong as to demonstrate that he is right. He very properly points out that the water coming from a surface condenser is not distilled or pure water in the chemical sense; but that, on the contrary, it contains air, carbonic acid gas, etc. In a word, pure distilled water is never used at sea in boilers, and this being the case, we cannot say from experience whether pure water would or would not corrode a boiler. But he urges that it is certain that it would not corrode a boiler, because the late Professor Crace Calvert found that distilled water which did not contain air or gases was without corrosive action on iron, a bright blade immersed in such water having become in some days merely here and there spotted with rust. This does not appear to us to be at all conclusive evidence against the corrosive powers of even pure distilled water. The spots of rust were found to occur at places where "small impurities in the iron set up galvanic action." Mr. Rowan will not maintain that boiler plates are free from impurities, and we see no reason to doubt that a boiler supplied with pure distilled water would quickly become spotted with rust, as did Professor Calvert's polished iron blade; and when spots of rust once begin to form, no one can say when the process of deterioration will cease. Besides, it must not be forgotten that Professor Calvert worked with cold water, not with hot; and one of the essential points in the arguments of those who consider pure water an enemy to boiler plates is, that the water must be heated to a high temperature. Again, does not Mr. Rowan beg the question a little when he asserts that air, or other gases, remains in solution in considerable quantities in a steam boiler? Is it not more than probable that the air finds its way, for the most part, to the steam space, and thence to the engine, almost at once? Is there, indeed, any good reason to believe that the water in a boiler which has been under steam for some days can contain much free air? We shall not attempt to decide, but we may say that Mr. Rowan has hardly proved his case.

After all Mr. Rowan has written, we are just a little surprised to find that he can suggest no new remedy for corrosion. The only cure is, he admits, to be found in covering all the surfaces of the boiler with a protective coating of some salt of lime. Every sea-going engineer in the kingdom was aware of this. The means which Mr. Rowan proposes for obtaining the required protection are somewhat novel, and consist in pumping a bucketful of thin whitewash into the boiler every now and then. Many engineers will prefer the

old plan of using a little sea-water from time to time as feed; but Mr. Rowan's scheme is extremely simple, and will, we have no doubt, work well. After all, however, it is somewhat unsatisfactory to find that a man of Mr. Rowan's great experience and research, aided, as he has been, by Dr. Wallace, a highly competent chemist, is unable to suggest any remedy for corrosion that has not been known and universally practised for many years with but indifferent success. If it is true that a scale $\frac{1}{16}$ in. thick increases the consumption of fuel by 15 per cent., as Dr. Rogers would have us believe, then Mr. Rowan's remedy for one evil introduces another of hardly less importance. What the marine engineer wants to get rid of is the necessity for obtaining and keeping, with infinite pains and worry, a scale in his boilers. When Mr. Rowan has failed to do this, we much fear that while the steam-engine endures, scale will have to be relied on as the sole agent which can prevent the rapid destruction of marine boilers.

THE CORROSION AND INCRUSTATION OF BOILERS.

From *The Engineer* of 19th October, 1876.

SIR,—I have refrained from replying to your leading article of September 15th, on "The Wear and Tear of Boilers," until now, in order that my paper, which you there review, might be published, and so in the hands of engineers generally, and that I might have the opportunity of learning what others had to say on the subject. Your review of my paper evinces a sufficiently kind feeling to leave me without desire to do other than acknowledge this and give it full weight in replying. It is on this account that I regret to have to point out that some of your remarks have rather the effect of misrepresenting the position I take up in that paper. I refer specially (1) to what you call the "remarkable fact of my passing over in silence the well-known truth that the deposit of lime salts in a boiler is due to the circumstance that these salts are less soluble in hot water than they are in cold water;" (2) to your account of "my theory of the corrosion of marine boilers working with surface condensers," which, according to this account, is that the action "is due to the presence in the water of grease and some gas," while I am "not very particular what gas" is meant; and (3) to your description of my "cure" for corrosion and the mode of applying it.

(1) Instead of ignoring the fact you speak of, I say, on page 614 of my paper, that Dr. Fischer has "proved from a number of analyses that various decompositions of the salts contained in waters take place under the influence of elevated temperature and pressure. Fischer quotes various authorities to show that gypsum gives off nearly half its water of crystallisation at temperatures up to 100 deg. Cent., and further proportions at higher temperatures, so that its solubility is greatly diminished. Above 140 deg. Cent. it becomes totally insoluble in sea-water, and at a lower temperature in fresh water, and hence is deposited as an anhydride. It is more easily soluble in water containing sodium or magnesium chloride in solution than in pure water." I might have referred to earlier demonstrations of these facts, but preferred to quote from Dr. Fischer's results because of the evident thoroughness of his work. I did not think it necessary to enter into the question of the use of brine chests, because I believe that the system of blowing off, even with such a modification, is pretty universally condemned—at least, it is disliked by all engineers who have learned the true relation of heat to work.

(2) How you could have gathered such an idea of my theory of corrosion from pages 626 and 627 of my paper, which treat of this part of the subject, I cannot understand. I had thought that I had made my meaning plain, but must have failed to do so. Let me point out here that I intended to indicate

very distinctly that the hydrochloric acid produced by the decomposition of the magnesium chloride in sea-water, and the carbonic acid gas which sea-water holds absorbed in considerable quantity, are "sufficient," as corrosive agents, "to account for most of the corrosion which occurs." And, besides these and the elements of high temperature and pressure which enter into the case, I desired to prove from the investigations of Stingl (described on pages 618, 619, and 620) that fatty acids in solution, obtained from grease, etc., have frequently had a considerable share in destroying boilers, and also that grease acts both directly, as in the cases mentioned by Stingl and by Jas. Gilchrist (p. 623), and indirectly by inducing galvanic action of the kind to which I referred on page 623, and 626. Filtering feed-water cannot, of course, arrest anything which exists in solution in that water, and therefore the mere exclusion of solid grease by such means cannot prove, as you would desire, that some corrosion is not due to grease acting as I represented its action in my extracts from Stingl's researches; but it is a great matter to exclude all solid grease and all metallic and other foreign particles from the boilers, and therefore I hold that every steamer using a surface condenser should have a filter for the feed-water. Carbonic acid and oxygen were the gases to which I repeatedly referred as being present in greater or less quantity in all waters, except really pure distilled water, so that I trust all doubt as to "what gas" I meant may be set at rest. I do not think that you are quite ingenuous in your use of my argument as to pure distilled water. I am not so foolish as to maintain that boiler plates are made free from impurities, and therefore have not stated the conclusion to which you seek to bring my argument, viz., that a boiler supplied with pure distilled water might not rust from that cause. What I endeavoured to prove was that the corrosion with which marine engineers are acquainted was certainly never produced by pure distilled water, because such distilled water has never been present to produce it, and because the character of the corrosion which has been produced is very different from that observed in Calvert's and Wagner's investigations with distilled water. Under the circumstance of the kind of experience which is available, I fear that it is idle to speculate as to what would be the effect of working a boiler with pure distilled water. As to the presence of air—*i.e.*, oxygen and carbonic acid—in the feed-water from surface condensers, the fact that such water is condensed in contact with air is sufficient evidence, I should think, for the majority of chemists that air is present in it. It is quite true that when this water is boiled, air is freed or partly freed from it; but in what you say on this subject you evidently forget that fresh quantities of air are being constantly brought back to the boiler by the condensed feed-water, and that the water in a boiler after a few days' steaming has probably been outside of the boiler, taking a little fresh air, several times during that period.

(3) My greatest dissatisfaction, I must say, is produced by your concluding remarks referring to my cure for corrosion and the mode of applying it. I do not think that what you say fairly represents my position.

On page 625 I pointed out the unstable character of the scale formed from sea-water, and on page 628 expressly contrasted with this the permanent scale —not of "some salt of lime," but of calcium sulphate and magnesium hydrate —to be produced from fresh water, which I proposed; and yet you write as if I had merely suggested a new method of doing what is done every day— *i.e.*, of making a salt scale. I am sure that those who read my paper at all carefully must in the main decide that you have not given much attention to that part of it. Your description of my method of forming this protecting coating is also very inaccurate. I do not advise or suggest that "a bucketful of whitewash should be pumped into the boiler every now and then"; but I say that the mixture for producing the coating can readily be fed in in the form of a thin whitewash, and should be applied to all boilers on the very first

occasions of getting up steam in them; and that by making an artificial scale with fresh water, as suggested, its thickness is quite under control, and when once hardened by heat, fresh water will not dissolve it, and thus steam can be generated in the best way. Even if a small quantity of sea-water should leak in, it is not likely that the coating would be injured. Under these circumstances, I confess to considerable astonishment at your remark, that what I suggest as a remedy "has been known and universally practised for many years with but indifferent success." I must reply that, except in some instances of our own, I do not believe that what I suggest has ever been practised at all as yet, but that it does offer to the marine engineer a means of getting rid of "the necessity for obtaining and keeping, with infinite pains and worry, a scale in his boilers." I must notice your parting shot at me on the score of the thickness and non-conductibility of the protective coating, and I have two things to say: First, I did not suggest or propose to form a scale $\frac{1}{16}$ in. thick; and, secondly, I do not consider a scale of that thickness as by any means thin. One special advantage of my mode of coating the boilers I state to be that the thickness is quite under control by it, and therefore the scale can be made thin, which is scarcely possible by the usual plan of working with sea-water. I suggested the coating in full view of Dr. Rogers' results, which I believe to be in the main correct, as they have not been disproved, so far as I am aware.

Péclet's principles, so far as I understand them, suppose, if they do not expressly stipulate for, a material which is a conductor of heat; for what avails the possession of a surface capacity of radiating heat if the heat cannot reach that surface through the body of the material? Would any one propose to make heat pegs of rock or of anything but a good conductor, like iron? Thus, though it may be true that a thin scale has in some cases actually increased the steaming power of a boiler, that certainly would not justify the conclusion to which your reasoning might lead us, that the thicker the scale we have the better, in order that it may act as heat pegs. I am afraid that when you penned your objection to my scale formation on the score of thickness and non-conductibility, you had forgotten your former remark, that "it has been shown that the presence of a thin scale has actually increased the steaming power of a boiler," on the score of which remark I might be pardoned for citing you as a witness in favour of my plan. For I have only to show that I form a thin scale to enable me to claim the advantage you mention. I should think that a scale of $\frac{1}{16}$ in. thick would be considered by most boiler proprietors as a positive nuisance; how much more one of $\frac{1}{4}$ in. or one of $\frac{1}{2}$ in.? You say that Dr. Rogers' results as to the effect of scales of these thicknesses on the temperature and combustion are "extremely incorrect." Can you tell me if any one has demonstrated them to be so, and if so, when and where? I have not verified them by experiment, but they seem to me to be not far off the mark.

As my paper was printed and in Messrs. Spon's hands before your article appeared, I could not adopt your suggestion as to declaring my acceptance in general of these results of Dr. Rogers. I should have been glad to have done so, had it been possible, for those who had, like you, some doubt on the subject. But while referring to this, I may be allowed to say that I think I might without difficulty have been understood as quoting only such results as I believed to be worthy of acceptance, or at least of consideration. I do not know that I have built upon the "isolated experiments or deductions of comparatively unknown experimentalists," but if you find that I have done so, I shall be glad that you point out the instances.

FRED. JNO. ROWAN.

[Before we wrote one line concerning Mr. Rowan's paper, we read that paper twice over word for word, and while commenting on it we

constantly referred to it. We are quite willing to admit that we have failed to understand Mr. Rowan. This is highly probable, because, as we have already pointed out, the great defect of the paper is its want of lucidity; and we confess that we still find ourselves, even with the preceding letter before us, uncertain whether we really understand our correspondent's meaning. For example, we have not the least idea what he intends to convey by the words, "a salt scale." Nothing of the kind has ever been used, to our knowledge, in marine boilers working with high-pressure steam to protect the surfaces. Salt water is introduced into such boilers in order that a thin, hard crust—not of salt, but of sulphate and carbonate of lime—may be formed on the iron. Under the conditions it is simply impossible that any coating of salt could be formed or maintained, and it appears to us that Mr. Rowan's plan of pumping in lime wash is identical in principle with that of pumping in sea-water. That is to stay, the composition of the resulting scale will be very nearly the same, whichever expedient we employ.—Ed. *E.*]

From *The Engineer* of 19th October, 1876.

Sir,—In your editorial note to my letter of last week you allude to a point of considerable importance, and I therefore ask the privilege of some of your space for a few words upon it. I have satisfied myself by the examination of a good number of analyses of boiler crusts and deposits, that all such, when deposited from sea-water, contain common salt, or chloride of sodium, and other ingredients soluble in fresh water. I believe, though I cannot speak dogmatically upon this point, that the proportion of these soluble salts in the crusts, and especially that of the chloride of sodium, increases in direct ratio to the pressure of steam carried in the boiler which has become coated with such scale. You will find these matters alluded to on pages 613 and 614 of my paper. Thus, a sea-water scale or crust contains more than sulphate and carbonate of lime, and this is a fact of great importance.

It is the presence of these soluble salts that renders sea-water scale so unstable, and that accounts for its ready removal by fresh water, or even by a larger proportion of fresh water in the boilers, as is obtained by "working fresh." This also explains why such scale can be preserved only by uninterrupted care in keeping the proper proportion of sea-water present in the boilers, for if the water becomes fresher the scale dissolves and disintegrates, and if the water is made more salt the thickness of crust is increased, and other troubles follow. All this involves, as you have said, "infinite pains and worry."

I have referred to this on page 625 of my paper, where I combat the opinion of Mr. Milln and some others who have asserted that the scale or crust formed from sea-water is insoluble; and it was with these facts before me that I denominated such a scale a "salt scale," in contrast to the coating which I recommend.

Fred. Jno. Rowan

The following is the letter referred to on pages 620–622 :—

THE CORROSION OF BOILERS.

To the Editor of "Engineering."

Sir,—I believe that the remarks on this subject in your article of October the 9th on "Boilers in the Royal Navy," will do good service by throwing

open a very important subject, and giving a proper direction to the thoughts of those who are interested in it.

There is no doubt that the experience you describe with the boilers in her Majesty's ships has been pretty generally known in the merchant service also, where indeed it has been that compound engines with surface condensers have been carried into general practice against such difficulties as are spoken of. I do not believe that these difficulties are as yet properly overcome in general practice, although in many instances this one of the corrosion of the boilers has been counteracted by the method now (as I understand you) to be introduced into the navy, viz., that of using salt water in the boilers to such an extent as to cause the formation of a protecting scale on their interior surfaces.

This, however, is evidently only a makeshift, useful enough until better means are adopted for protecting the boilers from decay, but a plan which has many disadvantages, not the least of these being that in it careless engineers have the means of doing serious injury to the boilers as well as of interfering with their economical and efficient working, by using too large a proportion of sea-water, and so allowing the formation of too thick a deposit of salt. Besides this it offers, as you remark, no solution of the nature of the operations which result in the corrosion of the boilers, and until these operations are understood it will be impossible to strike at the root of the evil. Moreover, as we are in marine engine practice advancing surely to the use of higher pressures of steam, and these as surely demand boilers having small sectional areas (and there are many considerations which render such boilers of great importance to naval service), there is additional reason at the present time for the investigation of this subject, because in view of boilers composed of small sections, such as water-tube boilers, the formation of saline deposit becomes increasingly objectionable.

I should like to give you the results of some observations which I think will be of some interest, and may add at the least a ray to the illumination of this subject. But first a few words as to your remarks.

You are undoubtedly right in ascribing to *pressure* the power of intensifying chemical action in general, and therefore *à fortiori* the corrosive action which takes place in boilers ; but while you admit pressure as an element in considering the action of distilled water upon the iron, you omit to give it its place with regard to the action of the acids which are set free by the heat of the steam from the fatty matters used in lubricating, and as a considerable quantity of oil and tallow passes daily through cylinders, etc., the quantity of these acids formed cannot be contemptible. I think that on this account you have not given sufficient place to the power of these acids, under the circumstances in which they can act, to act as solvents of the iron, and although it is no doubt true that they are "not capable of doing all the mischief," yet a great deal may be done by them as direct corrosive agents intensified in their action by high pressure and temperature, and also by their acidifying the water of the boilers, and so constituting it a more active medium for galvanic action. It is well known that dilute acid, as one of the elements of a battery, is much more active in exciting galvanic action than water alone in the same position is, and therefore we have another reason in this for regarding the presence of these fatty acids as a serious evil, and also a reason for giving greater weight than you allow to the power of galvanic action to assist in effecting corrosion.

"Tinning the condenser tubes has not," as you say, "arrested corrosion of the boilers," and I would add that neither has it arrested galvanic action in the boilers, for this is really caused by particles of brass or copper from the engine or condenser (from air pump, or valves, or piston rings, or condenser tubes, etc.), being carried into the boilers by grease, which collects several of them into one lump, and by this metallic lump being brought into contact

with the iron of the boiler in presence of the acid medium. A very active battery exists at the points where such lumps rest, and the iron under its action rapidly passes into solution and into the state of magnetic oxide, leaving a rough or honeycombed surface.

Pure water no doubt does dissolve iron, and the best *practical* demonstration of this action that I know was afforded us at my late father's works (the Atlas Works in Glasgow), where we found a range of horizontal multitubular boilers being rapidly acted upon by the Loch Katrine water which was used in them, and which, as is well known, is sufficiently pure to be used in chemical laboratories without distillation. As these boilers were used for working steam hammers and high pressure non-condensing engines, there was no chance of galvanic action such as I have described, and therefore the interior surfaces of the tubes were wasted *evenly*, until steps were taken by the introduction of limestone into the water of the boilers to arrest this action. The use of pieces of limestone in the boilers had the desired effect, so that it is not difficult to prevent the action of pure water ; but, in fact, this is an action which can exist only in a modified degree in marine practice, because the water of the boilers is not pure, but is always more or less contaminated by fatty and other matters, even where an admixture of salt water is not used.

Corrosion of the boilers was one of the principal causes of the failure of many of the early examples of the compound engines and boilers on our (Rowan and Horton's) plan, commencing with the s.s. Thetis, in 1858, whose boilers suffered from this action after a few years' work. This naturally led to much attention being devoted to this subject, and as these boilers were of the sectional or water-tube class, working at a steam pressure of 120 lb. per square inch, and using nothing but fresh water supplied by condensation when at sea, they offered opportunities for the observation of all the corrosive forces acting in circumstances the most favourable for them. When I tell you that six of these marine boilers worked for from eight to ten years at their original pressure of 120 lb. per square inch without repairs being necessary, you will readily understand that means were at length adopted which practically overcame in these boilers the corrosive action which had proved so disastrous in many of their predecessors and contemporaries.

The boilers of two steamers belonging to the London and Mediterranean Steam Navigation Company were among those on our system which were destroyed by corrosion after only a short life, and I have before me a copy of the report to the chairman of the Board given by Mr. Thomas Spencer, an analytical chemist who was consulted on the subject. Mr. Spencer attributed the corrosion entirely to the action of the fresh or distilled water, basing his opinion on the fact that the oxide of iron formed in contact with the steam and water was in great part *magnetic* (and not ordinary rust), while it had been observed that cast iron when acted upon by distilled water produced the same oxide. He proposed the use of a small quantity of silicate of soda or potash in the boilers as an antidote, but I am not aware if this was tried. I have given you my reasons for believing that galvanic action forms part of the forces at work in corrosion, and I think that such action sufficiently accounts for the formation of the *magnetic* oxide observed by Mr. Spencer, but nevertheless I believe that his hint as to the use of silicate of soda or potash in the boiler (or feed water, which amounts to the same thing) is a valuable one.

In the case of those boilers which worked successfully for so long a time, to which I have referred, the means used for the preservation of the boilers were simple. First, all the water discharged by the air pump was passed through a filter—a chamber in the feed tank filled with sand or charcoal—and this arrested all grease and all metallic particles on their way from the

engines to the boilers. Then pieces of zinc were inserted at various parts of the boilers, and as acid has a greater affinity for zinc than for iron the fatty acids expended their energy on the formation of salts of zinc, and the iron escaped while the zinc plates corroded away. I believe these precautions were accompanied by the occasional use of lime, a little of which was put into the feed water, but this was not of great importance in the case of these boilers, as they had the opportunity of replenishing their supply of fresh water pretty frequently in port, their voyage not being of long duration.

Lately I had an opportunity, during a voyage of the s.s. Propontis, which is fitted with our boilers working at 150 lb. per square inch, of observing the working of these plans, which, in her case, and also in that of the s.s. Constantin (formerly the Haco, a steamer trading from French ports, and now in her fifth year) are continuing to act satisfactorily. In the Propontis pieces of limestone along with the zinc were put into all the chambers of the boilers containing water, but on the suggestion of Mr. A. C. Kirk we have discontinued using the limestone in those chambers immediately over the fires, as it is very probable that the high temperature at these points sets the carbonic acid of the limestone free, and thus more harm may be done than good by the presence of the lime. The filter in her case is filled with the ordinary bone charcoal used in sugar refining, and the evidences of grease and particles of metal (brass and copper) arrested by it have been abundant. I have examined frequently the black grease taken from the exterior of the filter, and found it full of small metallic particles.

The increase of the density of the water to which you call attention was observed during the voyage, and somewhat baffled us, as it could not be accounted for. Your supposition that it is caused by the amount of iron in solution is not, I am afraid, the solution of the phenomenon, as I tested for iron by the colour test on more than one occasion, the water from the Propontis's boilers, which showed this increased density, but found no iron present in sensible quantity. Lime and zinc I did find present, but I am not sure whether I can now secure the samples of the water in order to have *quantities* estimated. I cannot at this moment lay my hands on the note of the densities recorded by the salinometer, but shall communicate them if they can be found. They were, however, sometimes considerably above the point at which water in boilers using salt water is supposed to be too salt, and must be blown off ; but as you describe, the taste was more nauseous than salt, but it was not astringent enough to indicate a large quantity of iron in solution. I do not think that we have sufficient information to lead to a definite judgment as to the cause of the increased density, though in continuous working the gross quantity of *water* being constant, the accumulation of all foreign matters which are not volatile must affect the density of the water more or less ; and perhaps some part of the effect may be due to the total expulsion (by repeated boiling) of all air or other gases held in suspension in the water.

As I did not observe your paper until Monday last, I have somewhat hurriedly thrown these thoughts together in order to help if I can in the elucidation of what is a very important subject in connection with engineering wherever high pressures and surface condensation are in use or wanted. In conclusion, let me bring some of the more important points together. As to the causes of corrosion these are, I believe :—

1. The action of fatty acids from the lubricants, intensified, by pressure and temperature, whether acting directly as solvents of the iron, or indirectly by
2. Galvanic action caused by particles of brass and copper carried by grease to the boiler, where, in contact with the iron and with the acidulated water, they form an active battery.
3. The action of distilled water in a modified degree.

For the prevention of corrosion, or counteracting these forces, we are led to the following remedies :

1. The use of zinc in the boilers to neutralise the acids.

2. The use of a filter for all the water passing into the boiler to arrest all grease and metallic particles ; and,

3. The use of lime or some alkaline mineral in the boiler, or in the feed tank, to neutralise the action of the distilled water, and also to give a base for any acid not neutralised by the zinc.

I quite agree with you, from the observation of the phenomena of the increase of density, that additional tests to that of the hydrometer or salinometer are required on board ship, and as the chemical tests for lime, common salt (or chlorine), and iron are very simple, it would be very advantageous if engineers knew how to use them, and did so when occasion offered.

Yours faithfully,

FRED JNO. ROWAN.

Glasgow, 21st October, 1874.

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